Aalto-yliopisto
Insinööritieteiden korkeakoulu

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Impact of quarter hourly imbalance settlement period on the Nordic physical electricity market

Thesis submitted in fulfilment of the requirements for the degree of Master of Science in Technology

Espoo, June 27th, 2019
Supervisor: Professor Sanna Syri
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Diplomityön tiivistelmä

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Työn nimi Viidentoista minuutin taseselvitysjakson vaikutus Pohjoismaisiin sähkömarkkinoihin ja kaupankäyntimenetelmiin	
Koulutusohjelma Sustainable Energy Systems and Markets	**Koodi** ELEC3048
Työn valvoja Professori Sanna Syri	
Työn ohjaaja(t) Timo Suhonen, FM	
Päivämäärä 27.6.2019 **Sivumäärä** 53	**Kieli** Englanti

Tiivistelmä

Pohjoismaisen synkronialueen taajuushallinta on yhä haastavampaa enenevien tasavirtayhteyksien sekä uusiutuvan sähkön tuotannon johdosta. Tässä diplomityössä käsitellään sähkömarkkinoiden sääntelyä, jonka tarkoituksena on helpottaa taajuushallintaa ja tehdä siitä markkinaehtoisempaa. Työn kannalta ratkaisevia sääntelyjä lähitulevaisuudessa ovat: velvoite muodostaa hinta päivänsisäisen markkinan kapasiteetille, siirtyminen yksitasemalliin, tasesähkön hinnanmuodostuksen tiukentuminen, päivänsisäisen kaupankäynnin sulkeminen taseselvitysyksikköön nähden sekä siirtyminen viidentoista minuutin taseselvitysjaksoon eli varttitaseeseen. Työn tarkoitus on eritoten arvioida varttitaseen vaikutuksia pohjoismaiseen sähkömarkkinaan, sillä tämä on sääntelyistä vaikutusvaltaisin.

Jotta tarkemman taseselvitysjakson vaikutuksia pystyisi kvantitatiivisesti arvioimaan, tutkin työssäni Saksan päivänsisäistä huutokauppaa, joka käydään viidentoista minuutin tarkkuudella. Analyysissä käytettävä data on peräisin vuodelta 2018. Kvantitatiivisen analyysin tarkoitus oli löytää järjestelmällistä käyttäytymistä sähkömarkkinaosapuolilta viidentoista minuutin tuotteilla. Analyysin menetelmä oli kerätä kuukausikeskihinnat jokaiselle päivän varttitunnille ja verrata niitä vuorokausimarkkinoiden tuntihintaan. Analyysin tulokset osoittivat, että päivänsisäiset hinnat ovat vahvasti syklisiä ja määräytyvät vuorokausimarkkinan tuntihintoihin pohjautuen. Päivänsisäisten varttihintojen volatiliteetin perusteella voidaan todentaa, että markkinaosapuolet käyvät pääsääntöisesti kauppaa oletetun tuotannon tai kulutuksen erotuksesta vuorokausimarkkinoilla jo allokoituun tukkusähköön nähden. Näin ollen viidentoista minuutin taseselvitysjakso on toiminut voimakkaana kannustimena välttää tasesähkön ostamista varttitunneilla, vaan ostaa se päivänsisäisiltä markkinoilta. Tulosten perusteella samaa varttitaseen vaikutusta odotetaan Pohjoismaisiin sähkömarkkinoihin, missä tämä vahvasti kannustaisi markkinaosapuolia käymään kauppaa myös varttitunnin tuotteilla.

Kirjallisuuskatsaukseen pohjautuen on näyttöä, että Saksan tukkusähkömarkkinoilla kaupankäynti varttitunnin tuotteilla sekä lähempänä toimitushetkeä ovat vähentäneet kantaverkon tasapainottamisen tarvetta. Yksi työn johtopäätöksistä on, että sähkömarkkinamalli vaikuttaa laajalti synkronialueen taajuudenhallintaan. Kuitenkin koska Pohjoismaat ovat jakautuneet yhteentoista tarjousalueeseen, samoja hyötyjä kuin Saksassa ei voida odottaa Pohjoismaissa ilman laajamittaisia muutoksia annettavien sähkönsiirtokapasiteettien resoluutioon. Ihannetilanteessa sähkönsiirto tarjousalueiden välillä määräytyisi varttitunnin tarkkuudella, jatkuvalla ramping-reunaehdolla. Lisäksi tasavirtakaapeleita olisi mahdollista käyttää tarjousalueiden välisien taajuuspoikkeamien netottamiseen. Kuitenkin optimaalisesta tarjousalueiden välisestä sähkönsiirtoyhteyksien käytöstä viidentoista minuutin taseselvitysjakson aikana on tehtävä lisätutkimusta.

Avainsanat Sähkömarkkinat, varttitase, päivänsisäinen markkina

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Diplomityön tiivistelmä

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Title of thesis Impact of quarter hourly imbalance settlement period on Nordic physical electricity market

Master programme Sustainable Energy Systems and Markets **Code** ELEC3048

Thesis supervisor Professor Sanna Syri

Thesis advisor(s) Timo Suhonen, FM

Date 27.06.2019 **Number of pages** 53 **Language** English

Abstract

Increasingly interconnected Nordic synchronous area coupled with increasing amount of intermittent generations poses a challenge to power system balancing. This thesis examines a set of regulatory measures which are to be implied for Nordic electricity markets to ease the balancing of the grid and possibly make it increasingly market based. The regulatory changes identified in the thesis are introduction of intraday cross-zonal capacity pricing methodology, introduction of one balance model, tightening of imbalance settlement pricing, introduction to rolling gate closure with relation to market time unit and most importantly introduction of 15-minute imbalance settlement period. As 15-minute imbalance settlement period is considered the most fundamental change, the purpose of thesis is to assess the impact of it to Nordic electricity market.

In order to quantitatively assess the impact of quarter hourly imbalance settlement period to Nordic electricity markets a German quarter hourly intraday auction was studied. The auction data used in the thesis is from year 2018. The purpose of analysis was to find systematic behaviour from market participants in quarter hourly trading. The method was to compile average prices of quarters over a month and compare them with day-ahead prices. It was found out that intraday auction prices possessed cyclical "zig-zag" pattern which revolved around day-ahead prices. After studying volatility of intraday auction prices, it led to conclusion that market participants were trading error of expected production and already allocated volume in day-ahead market. Based on the observation market participants were actively trying to avoid imbalance settlement by fixing their position in intraday market. The same impact of quarter hourly resolution is expected to the Nordic electricity market, which would push market participants to actively trade in the intra-hourly imbalances.

Based on literature review, it was found out that in German markets trading in finer resolution and closer to time of delivery has decreased the need for balancing of the power system. One of the key findings of the thesis was that power market design is strongly linked with balancing need of power system. It was identified that since Nordic electricity market is divided into eleven price areas, the same effect cannot be achieved from 15-minute trading as in German case without involvement of interconnectors. According to thesis ideally interconnector flow would be determined on 15-minute resolution, interconnector ramping would be continuous and HVDC interconnectors could be used for imbalance netting with central European markets. However, more research needs to be conducted on the topic on how interconnectors would be utilized in most efficient manner with respect to all stakeholders.

Keywords 15-minute imbalance settlement period, short term electricity markets, power system balancing, price dynamics, power markets, bidding behaviour

Acknowledgements

The subject for the thesis was chosen after discussions with various people about impactful regulatory changes to Nordic electricity markets. A special gratitude to European Market Coupling Operator Oy for support and contribution to developing the topic and guiding me through writing the thesis. I also want to express my gratitude to my Professor Sanna Syri and guiding Professor Lasse Leskelä in statistical work from department of mathematics and system analysis.

Espoo 27.6.2019

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List of abbreviations

ACER	Agency for the Cooperation of Energy Regulators
BRP	Balance Responsible Party
CACM	Capacity Allocation and Congestion Management guide
DSO	Distribution System Operator
EB GL	Electricity Balancing Guideline
EPEX SPOT	European power Exchange
EUPHEMIA	pan-European Hybrid Electricity Market Integration Algorithm
FAT	Full Activation Time
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal Operation
FRR	Frequency Restoration Reserve
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
HVDC	High Voltage Direct Current
IDCZGCT	Intraday Cross-Zonal Gate Closure Time
ISP	Imbalance Settlement Period
ISR	Imbalance Settlement Responsible
MARI	Manually Activated Reserves Initiative
NEMO	Nominated Electricity Market Operator
PICASSO	Platform of the International Coordination of Automated Frequency Restoration and Stable System Operation
PCR	Price Coupling of Regions
PX	Power Exchange
RR	Replacement Reserves
SDAC	Single Day-Ahead Coupling
SIDC	Single Intraday Coupling
TSO	Transmission System Operator
VRES	Variable Renewable Energy Sources
XBID	Cross-Border Intraday Platform

1 Introduction

The Nordic electricity market has historically been considered as well functioning electricity market. Having a complex topology of total of 11 delivery areas only in Nordics, three delivery areas in Baltics all interconnected, the market has allocated efficient flows over the borders and subjected electricity to socially optimal pricing.

The Nordic synchronous area is relatively small sized, compared to other synchronous grids in Europe. Compared to its size, it is heavily interconnected to other synchronous areas such as regional grid central Europe and regional grid Baltic. Due to availability of on average cheaper electricity, Nordics synchronous grid keeps becoming increasingly interconnected with rest of the Europe. Simultaneous increase in intermittent renewable energy generation in Nordics (mainly wind power but also solar generation) has subjected Nordic synchronous grid to systematic imbalances between demand and supply. As there has been no tool to address these imbalances, over the course of the years, frequency quality of Nordic synchronous area has constantly decreased, and the downward trend continues (ENTSO-E, 2019, sec. Frequency stability).

The European regulation has intervened, by obliging Nordic countries to imply some structural changes to electricity market such as transition to 15-minute imbalance settlement period and introduction to pan-European cross-zonal intraday auctions, further increasing European electricity market integration (EUR-Lex, 2017) (ACER, 2018a). Simultaneously in the Nordics, there has been proposed other changes to regulation around electricity markets, such as moving from two-balance settlement model to one-balance settlement model, changes to ramping, and changes to power system balancing (Statnett and Svenska Kraftnät, 2017). The underlying reason for this has been, that optimal electricity market outcome has deviated from optimal power system outcome.

The purpose of this thesis is to evaluate market impact of these regulatory changes, especially the impact of finer imbalance settlement period. There are already countries in Europe that have implemented 15-minute imbalance settlement period. Some of these countries have different market designs as Nordics, for example with availability of intraday auctions and shorter products. Previous research has shown that imbalance settlement period, thus the market time unit, has large impact on market structure and behaviour of market participants (Kiesel and Paraschiv, 2017) (Neuhoff et al., 2016). To fully understand impact of 15-minute imbalance settlement period in Nordics, the German intraday market prices are analysed against day-ahead prices in the thesis. This is believed to give insight how finer market resolution affects market behaviour of market participants. Therefore, the research questions of the thesis are as follows:

- First research question addresses behaviour of market participants, specifically how 15-minute imbalance settlement period will affect trading behaviour of market participants in the Nordics?
- Second research question addresses the declining frequency of Nordic synchronous grid, specifically what are the possible impacts of 15-minute imbalance settlement period to Nordic synchronous grid?
- Third research question is whether there are any other benefits from 15-minute imbalance settlement period specifically for Nordics in context of market coupling, system balancing or short proximity markets.

2 Electricity market model in the Nordics

European commission regulation (EU) 2015/1222, the guideline on capacity allocation and congestion management hereby referred as CACM urges Transmission System Operators (TSOs) and Nominated Electricity Market Operators (NEMOs) for close collaboration in order to further harmonize European electricity markets. One of the key purposes of the regulation, is to set the framework of co-operation for NEMOs, TSOs and regulatory authorities to establish single day-ahead coupling (SDAC) and single intraday coupling (SIDC). CACM urges electricity markets to operate to maximize social benefit from electricity trade.

2.1 Day-Ahead Coupling

The way of integrating different electricity markets via implicit auction system is called market coupling. The main benefits of market are shared order books of different power exchanges (PXs) or geographical areas thus improving the liquidity of the market, also optimizing cross-zonal flows. In other words, in coupled markets the supply and demand orders are not confined to local territorial area. This allows market clearing based on aggregated supply and demand with cheapest merit order, only being restricted by constraints of transmission network. When two separate markets with price difference and cross-border interconnection are coupled via implicit auction, the prices of these two markets will converge. If there is enough interconnector capacity between markets the prices will fully converge. However, if the interconnector capacity is insufficient, the bottleneck will be formed, and markets will remain separate price areas. Nevertheless, even in case of the bottleneck, the prices will converge with respect to the cross-border flow. One market will experience price increase, therefore gain in producer surplus and loss in consumer surplus. Respectively the other will experience price decrease, therefore gain in consumer surplus and loss in producer surplus. However, when these two markets are considered as one, social welfare of the market is maximized. The purpose of market coupling is to maximize social welfare. (Gómez, 2016)

The price coupling of regions (PRC) is initiative of eight European power exchanges. The purpose of the project is to develop a single price coupling solution to calculate day-ahead electricity prices and flows across Europe. One of key achievements of the PCR project is the development of a single price-coupling algorithm EUPHEMIA. The EUPHEMIA has been developed to perform the market coupling of the day-ahead markets in the PCR region, essentially the most of Europe. Although each PX collects the orders of market participants separately, those are submitted simultaneously to EUPHEMIA shortly after day-ahead gate closure at 12.00 CET. The EUPHEMIA matches the orders in concordance with prices to be published such that:

1. The social welfare, i.e. consumer surplus + producer surplus + congestion rent across the regions generated by the executed orders is maximal.
2. The power flows induced by the executed orders, resulting in the net positions do not exceed the capacity of the relevant network elements.

Hence, the Day-Ahead auction is cleared once a day by PXs' developed algorithm EUPHEMIA to allocate uniform pricing, positions of market participants and cross border flows for the next day. The clearing is set to optimize social welfare with respect to available cross border capacity and other grid constraints, such as ramping.

The pan-European day-ahead coupling has been a success. Apart from transparent prices and increased market liquidity, a notable accomplishment has been increased economic efficiency of interconnectors. In 2010 only 60.7% of interconnector flow was in right economic direction (price difference >1 €/MWh), whereas by 2017 it was 86% (C. ACER, 2018, chap. 5). Essentially these figures tell, that electricity is systematically flowing from low price areas to high price areas. As a result, over the past 8 years thanks to Day-Ahead market coupling, EU consumers have gained significant welfare benefits.

2.2 Intraday coupling

To comply with the requirement of CACM article 51, the implementation of single intraday coupling, European PXs and TSOs have jointly developed a pan-European IT-platform for continuous intraday trading, the XBID platform. The XBID platform facilitates continuous matching of market participants' buy and sell orders in the shared order book by utilizing cross-border capacity where available. The order book is shared among all regions participating in the market, ranging from Portugal to Finland. The TSOs provide cross-border capacity to capacity management module, which calculates available transmission capacity as trading occurs. (ENTSO-E, 2018a)

In the XBID, the different markets are coupled via implicit continuous capacity allocation method. This means that order book of market area A is visible to market area B's order book only if there is capacity between these two market areas. After each trade across market areas, the transmission capacity available for intraday trades is updated, it decreases in direction of the transaction and increases for trades in opposite direction. If required transmission capacity to execute a transaction is no longer available, the order books between area A and B are no longer shared. As a result, market participants of both market areas A and B can trade only locally. (Alexander von Selasinsky, 2014)

It is important to note, that continuous intraday solution fundamentally differs from auction mechanism, as the market is not cleared by third entity such as PX, rather market participants clear the market themselves. Term continuous refers to market being constantly open for buy and sell orders. The trades occur when matching criterion are met, which generally are quantity and limit price. Limit price is either the indicated maximum willingness to pay for quantity of electricity specified (bid) or the minimum willingness to sell volume electricity specified (ask). Eventually continuous intraday market participants develop an order depth for each product available. Order depth means that both buy and sell orders, which do not satisfy matching criterion, are sorted by highest limit bid price and lowest limit ask price. The highest indicated willingness of buyer to pay for electricity is therefore not sufficient to engage the lowest willingness of seller in transaction for current product. If two orders with identical price are placed, the order that was placed first will be matched first to an order that either exceeds or is exact to limit price. (Alexander von Selasinsky, 2014)

As continuous trading implies that trades can be settled whenever a market participant accepts an offer of another market participant, it can be said, that intraday market is a race of speed, as trading occurs on first-come-first-serve principle. On one hand this can be recognized as advantage, since it allows market participants to trade whenever they can expect benefits from trading up to the gate closure of a product. In other words, all possible market information, such as wind forecast or electricity demand, can be utilized real time and allowing market participants to fix their position accordingly. Article by Richard Schraff argues that intraday trading can facilitate the integration of vRES, as production forecasts closer to delivery hour are more precise than day before in day ahead market (Scharff and Amelin, 2016). Overall, an efficient ID electricity market requires sufficient market liquidity, because it enable market participant's access to a larger portfolio of bids and offers to meet their balancing needs. As for the integration of renewable resources, intraday liquidity is crucial for optimal integration. Without sufficient liquidity there will be no counterparty for renewable generation holders to fix their position with, thus leaving them out of balance. (C. ACER, 2018, chap. 4.2)

On the other hand, the great disadvantage of continuous trading is a lower allocative efficiency due to it's first-come-first-serve nature. The price of matched trades depends on prices of submitted orders; after a trade is matched another trade can only be matched from orders remaining or new orders. There is thus no uniform pricing for market areas, which means, that some trades on with positive welfare contribution might not to be realized while trades with negative welfare contribution might be realized (Scharff and Amelin, 2016). Essentially, there is no systematic approach to market clearing in intraday; hence, there is no guarantee of welfare maximization to occur.

From the system point of view, another disadvantage of continuous intraday market is that it has no mechanism embedded to reflect cross-zonal capacity pricing. In essence, XBID platform is made to trade volumes and sets intraday capacity price to zero. This leads to a problem that continuous intraday market does not reveal the value of cross zonal capacity when it's scarce. Here is an illustration. Capacity between two adjacent market areas A and B has been used by trading three hours before delivery, since area A has cheaper electricity than area B. One hour prior to delivery electricity has become scarce in area B, and some market participants would want to pay more for cheaper electricity from area A. In such situation, due to nature of implicit allocation, the market participants value also capacity more than two hours prior. Thus, they are also willing to pay more for it than two hours prior. Their willingness to pay more, however, is not reflected to the market as capacity is depleted and there is no mechanism to set price for it. Therefore, continuous intraday market is not incompliant with CACM Recital 22, which states: "Reliable pricing of transmission capacity should be introduced for the intraday market time-frame, reflecting congestion if capacity is scarce"(EUR-Lex, 2015). (ENTSO-E, 2017a)

An alternative market for continuous intraday market is intraday auction. Essentially, intraday auction has the same mechanism of market clearing as day ahead auction. The difference between intraday auction to day-ahead auction is that it occurs closer to the delivery just as name suggests. On the contrary to single intraday coupling, there has not been implemented any pan-European market model with intraday auctions, rather there are country specific market models involving intraday auctions. Such countries are for instance, Germany, Spain and Portugal, and Italy. The intraday auctions have different country specific products and different gate opening and closing times. Interestingly, in countries where intraday volumes account for most percentage of the demand such as Spain, Portugal, Italy and Germany intraday auctions are present in the market design and therefore facilitate organized ID market. Another common characteristic for these countries is high penetration of renewables. Intraday auctions are not necessarily a causation for increased intraday trading, but some market participants might value them, as they facilitate organized clearing at certain times.

According to study on trading behaviour by (Scharff and Amelin, 2016), that most of the continuous intraday trading is done manually and that not all market participants monitor the market around the clock. Although the data in the study is from year 2013, after which trading has increasingly automatized (Koch and Hirth, 2018), the continuous intraday trading nevertheless requires commitment to market monitoring. In case of intraday auctions, market participants only need to access the market at discrete timings of auctions. Even though intraday auctions can set value for capacity, most of the intraday auctions are inter zonal, with no access to cross zonal capacities as day-ahead auctions have, on the contrary. The exception here is Spanish and Portuguese border, but those are operated under the same monopoly power exchange. Intraday liquidity in general is mostly intrazonal both in auctions and continuous trading. The share of intra-zonal trades in auctions is 77% and in continuous intraday 78% across the Europe (C. ACER, 2018, fig. 25). Therefore, even though intraday auctions value cross-zonal capacities, for the most part they are not used in cross border trading as of today.

2.3 Role of Transmission System Operator

Transmission system operators (TSOs) operate the transmission grid of respective country or area. In other words, they facilitate the infrastructure for the power market. Large industrial customers, both producers and consumers as well as distribution grids connected to transmission system.

TSOs have many responsibilities, on one hand they are responsible for developing the grid and on the other operating it. Operating the grid is most importantly keeping the balance between production and consumption, i.e. maintaining the 50 Hz frequency. This is not so straight forward, however. Even though the transmission grids are national, the neighbouring transmission grids form synchronous areas. Essentially this means that frequency in the gird does not follow the national borders, rather the boundaries of synchronous area. Nordics form a synchronous area, part of which being Finland, Sweden, Norway and Denmark for the DK2 price zone. This setup longs for collaboration between Nordic TSOs and standardization of balancing methods and products. Frequently the collaboration between TSOs is driver for changes within synchronous area. Figure 1 below depicts Nordic synchronous area, and neighbouring synchronous areas as well as interconnectors connecting these.

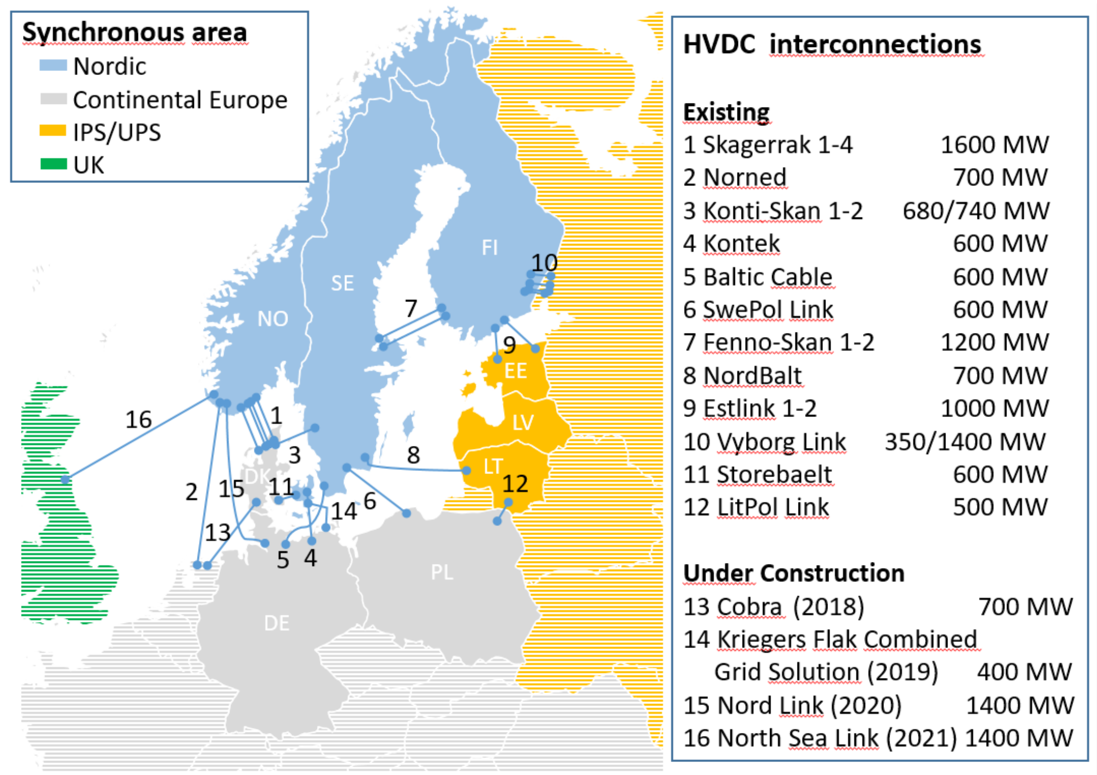

Figure 1: High Voltage Direct Current interconnectors from Nordic synchronous area (ENTSO-E, 2017b)

Another task of TSO is developing the grid. The TSOs can develop the grid within the market area but also cross-border. Local development essentially is improving the grid within the market area. Some of these improvements could be for instance to transfer power in larger quantities between delivery areas or within delivery areas, with less losses avoiding loop flows and internal bottlenecks.
The cross zonal development essentially means increasing interconnector capacity between market areas. If there occurs a situation, when adjacent market areas are not fully coupled due to lack of capacity on interconnectors, the market areas will create two separate price zones with price difference. This is known as bottleneck. TSOs collect congestion revenue over bottlenecks, according to following equation:

$$\begin{matrix} congestion \\ revenue \end{matrix} \left(\frac{€}{h}\right) = \begin{matrix} commercial\ flow\ on \\ day\ ahead\ market \end{matrix} (MW) * \begin{matrix} area\ price \\ difference \end{matrix} \left(\frac{€}{MWh}\right) \qquad (1)$$

The congestion revenue is distributed evenly between Nordic TSOs, meaning that respective TSOs split the congestion revenue in half. The regulation urges to spend all collected congestion revenue. Mainly the revenue is used for either investing into the interconnectors, thus alleviating the congestion, reduction of grid fees, countertrading or depositing for future investments. Underline of regulation being that received congestion rent should be invested. (Fingrid Oyj, 2018a)

Distribution system operators (DSOs) operate distribution grids, which deliver electricity to small businesses and residential customers. Whereas there is only one transmission grid per country and usually only one respective TSO, there are multiple distribution grids and DSOs within a country. In Finland for example, there are closer to 80 distribution grids, respectively around 80 DSOs. Nevertheless, 15 largest ones account for 70% of electricity distribution in terms of energy delivery. DSOs only deliver electricity to their customers, they do not own it, and thus they cannot sell it. The retail companies sell electricity to customers, whereas DSOs only charge the delivery fee. (Finnish Energy, 2014)

An important role of DSOs in all Nordic countries is consumption metering. Essentially all Nordic countries (Finland, Sweden, Norway, Denmark) have some form of regulation that obliges the DSOs, sometimes the customer, to meter the consumption of electricity hourly. There are country specific exemptions for some sites not to be metered hourly, but the baseline is that most of the consumption is metered hourly. The meters are read either once a day or once a week depending from country. (NordREG, 2014) The DSOs meter the consumption data of the customers and share the information with retailers, which further use the information when acting in the electricity market. Market participants have been extremely satisfied with such arrangement, as all market decisions can be based on metered data, which diminishes greatly the uncertainty of estimation (Energiavirasto, 2018). For example, estimating the energy demand of residential customers is important factor in buying correct amount of energy from the wholesale market. The metered data aids to choose correct quantity by providing information on consumption behaviour.

2.3.1 Balancing markets in Nordics

TSOs are responsible for balancing electricity production and consumption in the transmission grid. Instead of actively using own generation assets TSOs purchase balancing services, sometimes referred to as balancing reserves, either as balancing energy or capacity. Reserves generally refer to production or consumption assets which can either increase or decrease load in the grid in fixed amount of time. There are several markets where different kinds of reserves can be acquired. Although, balancing markets are mostly national, in Nordics the balancing products are essentially the same, with some country specific nuances. Generally, balancing reserves are divided into three categories: Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR) and Replacement Reserve (RR). Replacement reserves are not used in Nordic power system.

FCRs are automatically activated reserves triggered by deviation in frequency from nominal value. There are two types FCRs, Frequency Containment Reserve for Disturbances (FCR-D) and Frequency Containment Reserve for Normal Operation (FCR-N). The FCR-N is continuously used reserve to contain frequency in between 49,9 – 50,1 Hz, whereas FCR-D is only activated when frequency falls below 49,9 Hz. Both reserves are activated automatically. In Finland, the FCR is attained either from neighbouring countries via interconnectors or from domestic suppliers based on yearly or hourly auctions. The yearly auction is held on autumn to acquire reserve capacity for next year and daily auction each day at 18.30 for next day on hourly resolution. The results from latter auction are published at 22.00 EET. The FCR market is capacity market, meaning that only capacity is traded for the reserve, not the energy itself. Upon activation of reserves, the realized energy expenditure is billed separately. As FCR-D reserves are rarely activated, FRC-N reserves are essentially fine-tuning of frequency, where generation sites adjust their power output to maintain nominal frequency.

FRR can be divided into two categories, Automatic Frequency Restoration Reserve (aFRR) and Manual Frequency Restoration Reserves (mFRR). The aFFR reserves are automatically activated when frequency deviation of Nordic synchronous area has reached certain threshold. aFFR is used to restore Nordic synchronous frequency to nominal value and release already committed frequency driven reserves. Although Statnett monitors the Nordic synchronous area frequency, the aFFR markets are national. aFRR markets are capacity markets, where only capacity is traded, and energy delivery actualizes upon activation of reserve.

The mFRR have same purpose as aFRR, only they are activated manually by operator. The mFRR comprehends from both balancing energy markets and balancing capacity markets. By balancing capacity markets TSOs secure that they have enough capacity for possible up-regulation. The capacity for the balancing capacity market is procured in weekly auctions. The capacity that is allocated for the balancing capacity market, shall not be sold as any other reserve type or traded in any other market. The balancing energy market, commonly referred to as balancing market, is the only market of all reserves where energy is traded. Depending by the balancing need of delivery hour, TSO manually selects cheapest bids from the merit order, forming balancing market price by the most expensive order activated during delivery hour. Unlike any other reserve type, balancing market has common liquidity pool in Nordic countries. For this market, market participants shall place hourly bids for the delivery hour latest 45 minutes before the start of delivery hour. The up-regulation and down-regulation bids are placed separately, thus price for up-regulation and down-regulation is formed separately. In balancing market, the bids are standardized by full activation time (FAT) of 15 minutes. In other words, as balancing bid has been manually ordered by TSO, the asset must run on full capacity in no longer than 15 minutes.

2.4 Imbalance settlement structure

The purpose of imbalance settlement is to establish a financial balance of delivery hour in electricity market. The imbalance settlement is a financial settlement mechanism for charging or paying balance responsible parties (BRPs) for their imbalances. The imbalance settlement is always calculated over fixed unit of time. As the purpose is to financially settle imbalances of parties within delivery hour, the resolution of imbalance settlement period (ISP) is one hour.

In the Nordics, specifically in Finland, Sweden and Norway, a company named eSett Oy is imbalance settlement responsible (ISR). ISR thus eSett Oy is responsible for performing imbalance settlement and invoicing of Balance Responsible Parties (BRPs) for imbalances. A BRP is a company that has valid balancing agreement with TSO and valid imbalance settlement agreement with eSett. Each BRP has a balance obligation, i.e. an obligation to continuously plan and achieve balance between the electricity supplied and withdrawn by one or several producers or consumers and perform financial settlement for any of imbalances arising from these parties. Every electricity market participant must be assigned to a BRP, in order to participate in electricity market. The BRP is responsible for submitting hourly plan for specific regulatory object, such as power plant, 45 minutes before delivery hour to the TSO. TSO will then forward the binding production plans to eSett. If BRP participates in any of balancing or reserves markets host by TSO, TSO will report services provided by BRP to TSO. TSO sends the data to eSett, which will be further utilized in imbalance settlement.(eSett Oy, 2015)

The Nordic imbalance settlement model is structured by two separate balances for production and consumption, which are calculated and settled separately. The production imbalance volumes are calculated according to equation (2):

$$Production - \begin{matrix} Planned \\ production \end{matrix} \pm \begin{matrix} Production \\ imbalance \\ adjustment \end{matrix} = \begin{matrix} Production \\ imbalance \end{matrix} \tag{2}$$

The consumption imbalance volumes are calculated according to equation (3):

$$Consumption - \begin{matrix} Planned \\ production \end{matrix} \pm Trade \pm \begin{matrix} Consumption \\ imbalance \\ adjustment \end{matrix} \pm \begin{matrix} MGA \\ imbalance \end{matrix} = \begin{matrix} Consumtion \\ imbalance \end{matrix} \tag{3}$$

The imbalance settlement is for the most part based on the metered data provided by DSO. The DSOs are obliged by law to provide measurement data of electricity production and consumption needed to fulfil the settlement purposes (Finlex, 2013). Specifically, the DSO is responsible for reporting hourly-metered data per production unit to eSett, which will then aggregate metered data on BRP level. Same applies for consumption, except that consumption metered data is aggregated on retailer level, and further assigned to BRP.

Nominated electricity market operator (NEMO) is obliged to report the Day-ahead and Intraday trades to its customers and eSett and flows to the eSett and TSOs respectively.

2.4.1 Imbalance fees

Currently in the Nordics, production and consumption balances are settled separately. Imbalances occurring from production are priced according to two-price model, which means that positive and negative production imbalances have different prices. During up-regulation hours, the price of negative production imbalance equals to up-regulation price of balancing market, whereas the price of positive production imbalance is the power exchange Day-Ahead price. The up-regulation price is always higher than the PX day-ahead price. In down-regulation hours, the price of negative production imbalance is the PX day-ahead price and the price of positive production imbalances is the down-regulation price, which is always lower than the PX day-ahead price. (eSett Oy, 2015)

If both up-ragulation and down-regulation are carried out during the delivery hour, the regulation direction of the hour is the direction in which more energy was regulated. In hours where no up or down regulation is applied, negative and positive imbalances are both priced with the PX market price. (eSett Oy, 2015)

Imbalances in consumption balance are priced according to one price model. This means that positive and negative consumption imbalances have the same price. Simply, in up-regulation hours, the price of both negative and positive consumption imbalance is the up-regulation price. Likewise, in down-regulation hours, the price of negative and positive consumption imbalance is the down regulation price. If there is no regulation during the hour, the price of negative and positive consumption imbalance is the PX day-ahead price.

3 Legislative changes to market in near future

3.1 Imbalance settlement

Imbalance settlement structure is a framework for incentivizing BRPs to stay in balance, and therefore is a major contributor to a market design. In the near future, imbalance settlement structure is subjected to changes both on Nordic and pan-European level.

On November 23rd, 2017 EU commission in co-operation with ACER has released guideline on energy balancing (EB GL). The guideline also defines common rules for imbalance settlement. According to article 53 in Electricity Balancing Guideline (EB GL), all TSOs shall apply the imbalance settlement period of 15 minutes in all scheduling areas by the end of 2020 (EUR-Lex, 2017). From then on, all imbalances will be settled in shorter increments.

In the Nordics, the imbalance settlement model will change from two-balance model to single-balance model. Instead of calculating separate production and consumption balances per BRP, there will be only one balance per BRP. The purpose of this change is to treat producers and consumers evenly, but also to simplify settlement model for balancing providers or intermediary parties such as aggregators. The proposed and probable new imbalance calculation model is presented below (Pulkkinen, 2018):

$$Consumption + Production \pm Trade \pm \begin{matrix} Consumption \\ imbalance \\ adjustment \end{matrix} \pm \begin{matrix} Production \\ imbalance \\ adjustment \end{matrix} \pm \begin{matrix} MGA \\ imbalance \end{matrix} = \begin{matrix} Consumtion \\ imbalance \end{matrix}$$

(4)

The significant impact of single balance model is that no production forecasts need to be sent to the TSO 45-minutes before delivery. This in turn enables intraday trading for producers up to intraday gate closure, without influencing their balance position. The single imbalance settlement model is expected to be in use somewhere between late 2020 to late 2021. (Fingrid Oyj, 2018b)

The pricing of imbalance is changing as well. As there will be no longer production balance, the two-price model for production imbalances will disappear. Single imbalance pricing model will be applied from today's consumption imbalance pricing. According to Article 7 of All TSOs' proposal to further specify and harmonise imbalance settlement in accordance with Article 52 of EB GL, each TSO shall implement the use of single imbalance pricing for all imbalances (ENTSO-E, 2018b). This can be interpreted, that also netted imbalances will be subjected to imbalance price. In other words, imbalances during ISPs with no up or down regulation will be fined by imbalance price rather than PX market price as of today. There is no framework established yet how the imbalance price will be calculated for these ISPs (Fingrid Oyj, 2018b). The change is significant, as according to ACER annual market monitoring report (C. ACER, 2018) over 70% of imbalances are netted in Nordic synchronous area. The estimated impact is that as imbalance price is less favourable for BRPs than PX market price, the change will incentivize BRPs to avoid imbalance settlement and fix their position in Intraday.

3.2 Balancing and reserves

Balancing markets on both Pan-European level as well as the Nordics are undergoing large structural changes. The balancing market is expected to be more flexible, more integrated, cheaper, and most importantly facilitate new ways of balancing such as demand response. (EUR-Lex, 2017) In order to address the new challenges, the European Commission in co-operation with ACER released a guideline for electricity balancing in November 2017. The regulation urges TSOs and DSOs to be in closer collaboration in order to integrate and harmonize balancing processes both internally and cross-zonal. The influence of EB GL regulation has implications on pan-European level, such as market integration of balancing markets and reserves. In addition, Nordic TSOs have common projects that aim to harmonize Nordic balancing.

On the European level, the fundamental change is that some of reserve types shall operate on common pan-European platforms. With respect to EB GL requirements, ENTSO-E has established multiple projects to cope with new regulation. The common characteristic to these projects is integration of balancing platforms and setting common rules for balancing. The Nordic TSOs are taking part in two of these projects, MARI and PICASSO. The platform for International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) is a project that targets implementation and operation of a Platform for automatic Frequency Restoration Reserves (aFRR). This platform is designed to be compliant with CACM, essentially integrating most of aFRR markets over Europe (ENTSO-E, 2018c). Manually Activated Reserves Initiative (MARI) is another pan-European project Nordic TSOs take part in, which essentially has the same scope as PICASSO, just for different market, the mFRR. As these projects have been announced only recently, the go-live date is yet unknown.

In addition to pan-European projects, the Nordic TSOs have also tightened collaboration around balancing markets in Nordic synchronous area introducing Nordic Balancing Concept and roadmap. The key changes are targeted towards frequency restoration reserves. A fundamental structural change to all FRRs is to comply with 15-minute imbalance settlement period, meaning that balancing products will shift to finer 15-minute resolution. The mFRR balancing market is expected to change from hourly to quarter hourly resolution at the same time as 15-minute imbalance settlement period is introduced, during Q2 2020. (Uusitalo, 2019) Other key deliverables are to merge national aFRR and mFRR capacity markets into two new common Nordic aFRR and mFRR capacity markets by Q2 2019 and Q4 2019 respectively. In addition, a completely new quarter hourly balancing energy market, namely common aFRR energy market is planned to be introduced by Q1 2021. (Statnett, 2019)

There are also plans to change the gate closure of mFRR energy market. On 18th of December 2018 European TSOs have jointly proposed the gate closure of standard mFRR balancing energy product bids to be 25 minutes prior to beginning of quarter for which the bid is placed. This is expected gate closure time when 15-minute ISP is valid in Nordics. (ENTSO-E, 2018d, pp. 18, Article 8)

3.3 Intraday

The Chapter 6 of the CACM Regulation specifies requirements for the SIDC, including a single methodology for pricing intraday cross-zonal capacity. CACM requirement on capacity pricing is to establish efficient pricing and reflecting market congestion, based on actual orders. (EUR-Lex, 2015, chap. 6) On 10th of August of 2017 all TSOs have sent a proposal to regulators on cross-zonal intraday capacity pricing methodology, which has been approved by ACER decision on 24th of January 2019. TSOs proposal was to establish a hybrid model for intraday capacity pricing. This means that in addition to continuous intraday market, there will be complimentary intraday auctions which would effectively price the capacity. The decision states that there will be three additional intraday auctions after day-ahead for next day's delivery. First to be held in the day D-1 with gate closure at 15:00, second one on D-1 with gate closure at 22:00 and the last one on day D with gate closure at 10:00, all times in CET. The decision, however, does not specify the resolution at which these intraday auctions should be held, thus leaving a big gap in understanding future market design. Given that ISP will move to 15-minutes, as will the balancing market, the market participants are put under pressure to trade on 15-minute intraday products instead of hourly intraday products. It is therefore somewhat unreasonable to value the capacity on hourly resolution, as the full advantage will not be taken from the hybrid model. Moreover, according to the recital 12 of EB GL: "the harmonization of imbalance settlement period to 15 minutes in Europe should support intraday trading and foster the development of a number of trading products with same delivery windows". With accordance to the recital 12 and deduction above, this thesis assumes that intraday capacity pricing methodology, specifically intraday auctions, will be held on 15-minute resolution. As there has not been any intraday auctions in the Nordics, it is a great change to a market design.

Another structural change that will affect continuous intraday market is introduction of rolling cross-zonal gate closure time. On 24th of April of 2018 ACER has released decision on all TSO's proposal for intraday cross-zonal gate opening and intraday cross-zonal gate closure times (IDCZGCTs) (ACER, 2018a). According to the article 63 of the decision, the IDCZGCTs should be in relation to the start of the relevant intraday market time unit. It is further specified in article 64, that the relevant intraday market time unit corresponds (i.e. is equal) to the imbalance settlement period, given that the ISP is the same across the border. Theoretically, as all countries should implement EB GL requirement of moving to 15-minute ISP latest by 2021, the whole continuous intraday market should operate on 15-minute IDCZGCTs. The regulation only obliges the gate closure to be in relation to ISP, sometimes called rolling gate closure, however, it does not specify how long before delivery should the IDCZGCT be. Already today the IDCZGCT is one hour before delivery, the change that will occur is that there will be four IDCZGCTs within an hour. The remoteness to start of the delivery might remain the same. Also, countries have a right to apply for an exemption of 15-minute ISP until year 2025, therefore this thesis will not assume that whole pan-European intraday market will move to 15-mintue ISP. Nevertheless, as all Nordic countries are planning to implement 15-minute ISP at the same time, and central European countries on the other side of Nordic interconnectors such as Germany and Netherlands already have 15-minute ISP, it can be assumed the whole intraday market around Nordics will move to 15-minute gate closure time. The impact is that market participants will have unified amount of time to utilize market information for each tradable quarter. Second significant change is that the quarter hourly gate closure will be cross-zonal, which means that there will be no local markets on quarters before gate closure unless the capacity is used on the border. This creates deeper order depth closer to gate closure, which increases market efficiency, as the merit order is larger before gate closure than previously.

3.4 Day-ahead

ACER released decision on algorithm methodology on 26th of July 2018. According to Article 4 of the decision, by August 2022 the price coupling algorithm shall be able to support all future requirements for algorithm methodology and all NEMOs shall be compliant with it (ACER, 2018b). Specified in Annex II, one of the requirements is that for each bidding zone, the price coupling algorithm shall be able to facilitate orders for several market time units, such as 15, minutes 30 minutes and hourly (ACER, 2018c). This statement implies that Day-Ahead algorithm, and thus all NEMOs being part of single day-ahead coupling, should be able to facilitate 15-minute resolution products in day-ahead. However, the regulation does not explicitly state whether the 15-minute resolution products should be implied cross-border, i.e. over interconnectors. Essentially the regulation states that PXs should by August 2022 provide 15-minute contracts, but these contracts can be provided in local auctions. This arrangement would not have any benefit from market coupling, nor from interconnectors, as those are not applicable in terms of regulation. Therefore, by the means of regulation it has been undefined, when or if SDAC as we know it today will move to 15-minute resolution.

4 Purpose of 15-minute ISP

There are areas in operating transmission grid to which quarter hourly resolution may be a great aid. First one, is the balancing of the transmission grid. The grid constantly needs balancing. If it wouldn't, it would imply that BRPs are always in balance with each other. As this is not always the case, centralized balancing implies costs, the cost of balancing. Seemingly, the TSOs pay the costs of balancing, as they run the balancing market and procure the reserves. In the very end, the TSOs are responsible for stable frequency in the grid. However, TSOs can recover the costs from market participants in grid fees or from imbalance fees or any other fees paid to eSett (eSett Oy, 2015, chap. 8.1). Therefore, eventually the market pays for balancing, the BRPs themselves. As this is the case, it would be reasonable to subject the need of balancing to market forces, by making BRPs responsible for their own balance. From the system perspective, it would be beneficial that the need for balancing would diminish. Therefore, the 15-minute ISP is introduced, which is expected to shift responsibility of balancing more to market participants.
Another issue that 15-minute ISP could contribute to is addressing the structural imbalances of the grid. The underlying problem of Nordic synchronous area is that the grid cannot be balanced nationally, as each countries action within grid affect the whole Nordic synchronous area. The result has been that in the Nordic synchronous area, the quality of the frequency has been declining ever since middle 2000's (Nordic TSOs, 2016). Inefficient balancing does not solely cause the weakened frequency quality. Mostly it is due to systematic imbalances of the grid, which arise from very nature of assets in the market operated on hourly resolution.

There are situations discussed in next chapters, which explain why hourly model leads to inefficiencies in the market and balancing the grid. It is also discussed why introduction of 15-minute ISP, and complimentary 15-minute resolution on balancing market would address these inefficiencies.

4.1 Inefficiencies in balancing grid on hourly ISP

4.1.1 Netting imbalances within an hour

When market participants trade in the market, eventually they fix their position for the delivery hour. They may alter their position up to gate closure of intraday, but eventually they will end up with some final position, the scheduled production or consumption. In some sense, it is promise of energy delivery for the delivery hour. As of today, the realized production/consumption is measured over the whole delivery hour and settled within hourly ISP. The length of hourly ISP bares a problem. It allows market participants to deviate their actual power production/consumption from the scheduled production/consumption within the hour and still end up perfectly balanced. To avoid imbalance fees, BRP's actualized position needs to be in balance with scheduled position only by the last second of the delivery hour. Essentially, BRPs can be instantaneously out of balance over the hour as long as imbalance surplus and deficit even each other out by the end of the hour. However, the instantaneous imbalance of BRPs contribute to the imbalance of the grid and TSO could activate balancing bid or countertrade. In these cases, BRPs receive no penalty for their behaviour as they are in balance with themselves within the ISP, but there might be a cost for the system. In such situations, the actualized cost for balancing grid is not paid by the party that caused need for balancing. The situation is illustrated in Figure 4:

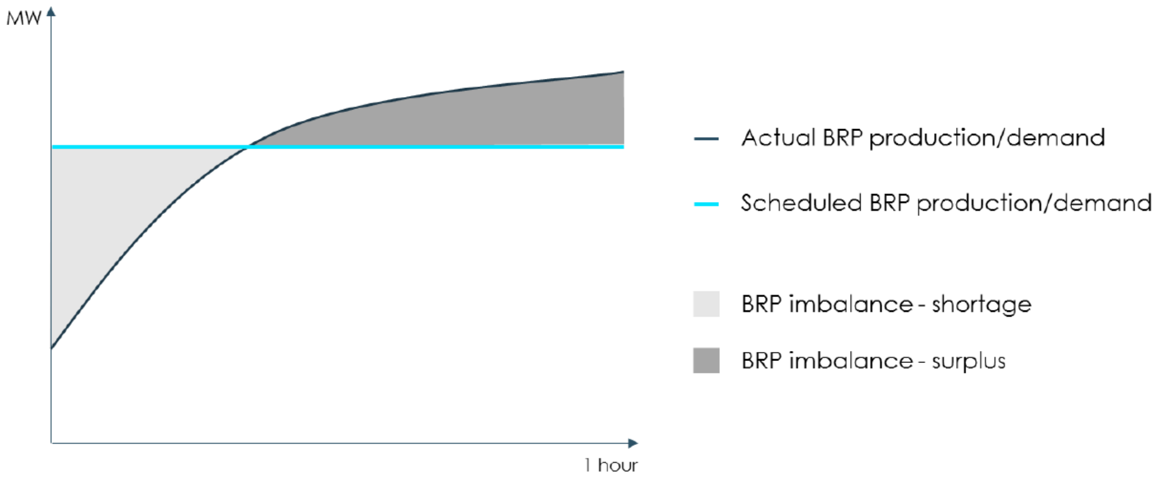

Figure 2: Example of BRP's opportunity to net intra-hourly imbalances (Copenhagen Economics, 2017)

In the figure 2 flat x-axis blue line represents scheduled BRP production/demand. It is the quantity BRP is obliged to deliver over one hour. It can be seen from the figure, that actual BRP production/demand, the black trendline, is not equal to scheduled one. In the beginning of the hour, BRP's actual balance is on a deficit while during the rest of the hour it is on surplus. If the surplus and deficit areas on the graph, the actualized over and under production/consumption energy, are equal, the BRP is in balance and faces no imbalance fee.

The situation is theoretical, as balancing products are activated with respect to state of the whole transmission grid, sometimes even whole synchronous area. In other words, micro imbalances of single BRPs not always result in macro imbalances of the system, as they can even each other out on micro level. Nevertheless, this phenomenon takes away responsibility of keeping grid in balance from BRP towards TSOs. Moreover, as of today, the balancing products are hourly. Thus, at least in theory; if system operator calls for balancing product, it might be in use for longer time than it is needed. The instantaneous imbalance of first 15-minutes of an hour, could lead to activation of hourly product. Thus, the product will run for 45 minutes extra, for cost that is higher than PX market price of electricity.

There are generally two causes for behaviour depicted in figure 2. First cause is when BRP can control actual production, a thermal powerplant for example. The market participant, BRP, sells some amount of electricity for each hour in Day-Ahead market for the next day. The scheduled production is stepwise, a fixed quantity over the hour, possibly differing each hour. The thermal powerplant cannot cope with radical changes of scheduled production, thus is ramped up and down with much smoother ramp rate. This could be situation in Figure 2, when BRP is ramping up it's generation for next hour, where presumably scheduled production is higher than during hour depicted in figure 2. Another cause is when BRP cannot control its output, either production (generally the solar or wind production) or demand. In such cases, market participant needs to estimate or forecast the aggregated position and fix the corresponding amount in market. Thus, when behaviour in figure 2 is extended over longer period, the situations described above lead to structural imbalances in the grid which will be discussed in chapter 4.2.

4.1.2 Price of an imbalance

The hourly price of the balancing market is determined by the most expensive bid activated within the current hour. Therefore, the price of imbalance of the whole ISP can be determined by most expensive quarter. This makes all imbalanced BRPs suffer the highest possible imbalance fee, although they might not have contributed to such occurrence. Figure 3 below illustrates a real-life situation on 22nd of January 2016 from Nordic balancing market.

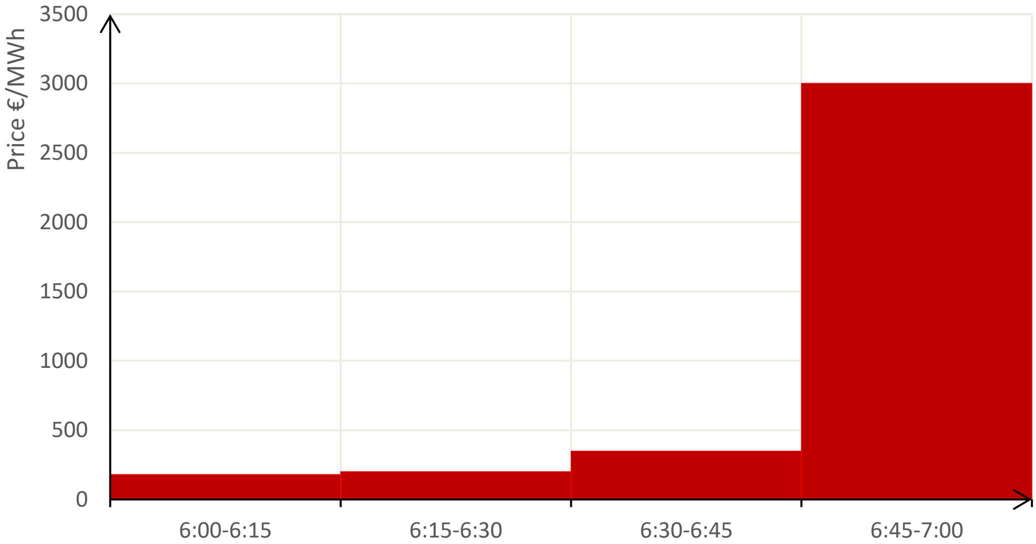

Figure 3: Balancing price formation in Finalnd at quarters on 22nd of January 2016 (Fingrid Oyj, 2018b)

On the first three quarters of an hour the need for balancing was moderate and stable. The prices of the most expensive activated bids were somewhat mutually aligned, priced around 300 €/MWh. On the last quarter of an hour, the need for balancing was such order of magnitude, that the most expensive balancing bid had to be activated, resulting in a price cap of 3000€/MWh. As 3000€/MWh became the final upregulation price for the whole hour, it led to the situation where price of an imbalance for the hourly ISP did not reflect the (cheaper) cost of balancing for the first three quarters. Thus, all BRPs had to pay the same imbalance fee regardless of when each BRP contributed to the imbalance within an hour. If 15-minute ISP had been introduced, only the BRPs that were imbalanced during last quarter would have to pay market cap price for imbalance. The imbalance fees would thus be evenly distributed.

More to the same problem, there are occurrences in the balancing market, when very small balancing bids are activated only for short amount of time, say one quarter of the hour. This however sets balancing market price, thus the imbalance fee, for the whole hour. Therefore, all BRPs within the hour need to pay balancing market price for imbalances that occurred only during short amount of time. This again leads to uneven distribution of costs of imbalance settlement.

4.1.3 Up-regulation and down-regulation within an hour

There are situations where during the same hour, TSO activates both up-regulation and down-regulation bids. Such situation occurred for example on 12th of July 2018 in Finland at 9:00-10:00 CET, where up regulation was activated for 60 MWh and down-regulation for -47 MWh.(Fingrid Oyj, 2019a) Because volume of up-regulation was higher than volume of down-regulation, the price of imbalance was the balancing market's up-regulation price. Thus, parties contributing to down-regulation imbalance are fined by wrong premises. Such kind of occurrences are rare. They however express a phenomenon, that examining grid balance over an hour is loose timeframe, as the balance cannot be controlled.

4.2 Structural imbalance of Nordic synchronous grid

4.2.1 Structural imbalance during hour shifts

The way today's energy market functions, for each BRP, the scheduled consumption or production is determined hourly. For some BRPs it changes each hour, more than for the others. Essentially it means, that in single point of time, particularly the point when hour turns to next one, BRPs are obliged to different scheduled flow for next hour compared to previous one. Therefore, the generation or consumption needs to be ramped up or down whichever way the next hour's position is allocated. Some assets can reach the scheduled production or consumption of next hour quicker than others, which leaves possibility for imbalances as there is no guarantee that all assets ramp with the same rate at the same time. Presumably, there is always some ramping needed to reach the next hour's scheduled production or consumption. Depending on asset's nature, there are some cases when BRPs can fix the same position for each consequent hour with block orders for example. Not all assets can ramp from scheduled production or consumption of previous hour to the next hour instantaneously, therefore the changes are done in advance. This frequently leads to situations when actual production/consumption of last quarter of previous hour is closer to the scheduled production/consumption of first quarter of next hour. This phenomenon results in so called imbalance jumps, where in order to reach next hour's equilibrium production or consumption, the ramp time around hour shift contributes to the imbalance. The phenomenon is illustrated in Figure 4 below.

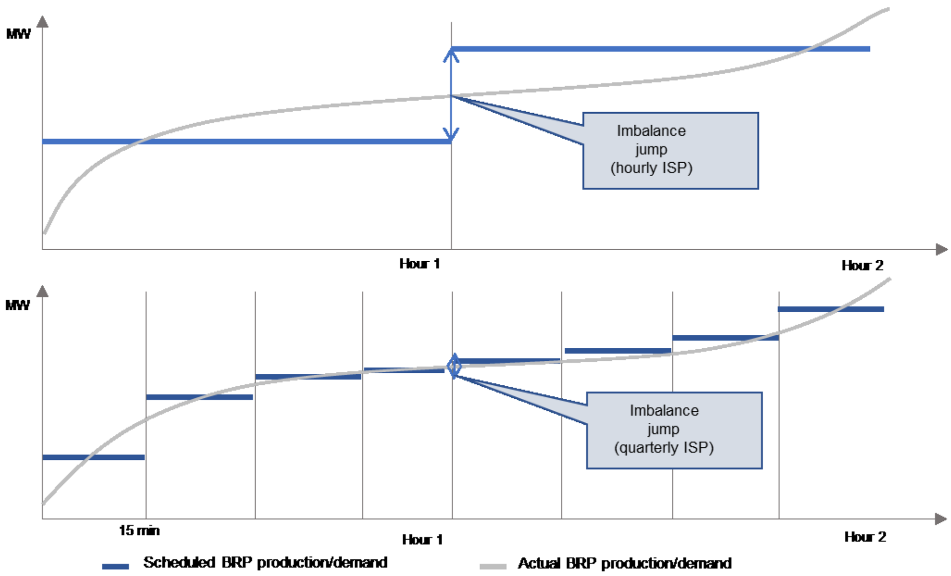

Figure 4: Illustration of imbalance jumps with hourly and quarter hourly ISP (Copenhagen Economics, 2017)

The upper part of figure 4 above depicts market behaviour of a BRP in an hourly imbalance settlement period. The situation is reminiscent to figure 2. The trendline is actual BRPs production/demand. In hourly ISP the market participant's scheduled position instantly increases when the hour 1 changes to hour 2, as can be seen from the figure. The market participant actual production/consumption, however, cannot comply with such change. The counterparty with whom the electricity was traded, different BRP, could potentially comply with such change. Say hydro power producers could ramp their production nearly instantaneously following the imbalance jump, thus leaving a large imbalance in the grid. If the 15-minute ISP would be introduced as is depicted in lower graph in figure 4, the scheduled BRP position would correspond to BRP's actual position closer to real time. This would not remove the imbalance jumps, but it would make them significantly smaller, as can be seen from the figure.

4.2.2 Structural imbalance with interconnector ramping

The same issue with imbalance jumps becomes particularly evident with interconnectors extending from Nordic synchronous area. As previously mentioned, the day-ahead auction determines the flow on interconnectors via implicit allocation with respect to social welfare maximization. The flow on direct current interconnectors to outside the Nordic synchronous area can be physically tuned. In order not to stress the power system, High Voltage Direct Current (HVDC) interconnectors have a ramping limit of 600 MW for each hour. (Copenhagen Economics, 2017) More specifically the ramping is only allowed to happen during ± 10 minutes around the hour shift. The maximum ramping speed currently is 30 MW power per minute, thus resulting 600 MW ramping limit over the 20 minutes. The interconnectors rarely reach ramping limits. When all interconnectors' flow is aggregated however, there are occurrences when total flow is dominant in some direction, inside or outside the Nordic synchronous area. Interconnector flow is determined by aggregated scheduled position of BRPs, essentially by the imbalance jumps. HVDC interconnectors ramp relatively quickly, 30 MW / minute / interconnector, thus following the imbalance jumps quite in real time. In order not to result in structural imbalances, rest of power system should keep up with the ramp rate of interconnectors. On more granular level the actual position of BRPs should follow scheduled position of BRPs much closer to real time, at least on aggregate not exceeding interconnector ramp speed. Figure 5 below illustrates changes in imbalances during hour shifts from year 2016.

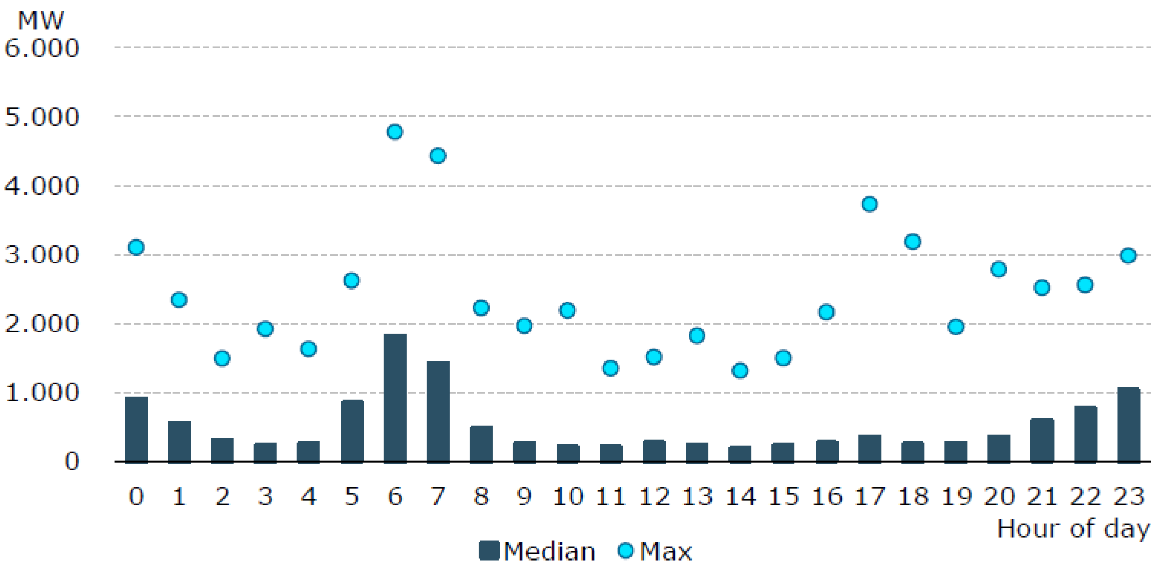

Figure 5: Nordic power system average imbalances at hour shift in 2016 (Copenhagen Economics, 2017, fig. 7)

The figure 5 above displays median and maximum imbalances during hourly shifts in the Nordics per hour, based on all imbalances in 2016. As is seen from figure, even median imbalances are quite large; 400 MW mostly but during morning peaks and day-change around 1000 MW. Maximum imbalances are of very impactful size, reaching many thousands of MWs. To balance these quantities actions from TSOs are needed more than during the rest of the hour, and even if no actions are taken the frequency quality will decrease, which has been the case for over a decade in Nordics already (Nordic TSOs, 2016, chap. 4). The important issue to understand is that these imbalances are systematic, stemming from structure of power market and imbalance settlement. Therefore, to address these errors, a systematic change needs to be imposed.

4.2.3 Systematic imbalances due to directional variables and forecasting error

There are different kinds of errors related to forecasting of either the RES or load. A research on wind power forecasting accuracy in Finland has identified two main sources that cause error in forecasting: level and phase errors. Level errors are caused by systematically erroneous prediction, whereas phase errors are caused by forecasting level of production correctly but failing to predict the timing of changes. (Holttinen et al., 2013) This ideology can be adapted to all forecasted variables in power system, including solar power and load, not just the wind power. The level errors, i.e. predicting the level of production wrong, are usually caused by badly configured forecasting model or error might be random. The phase errors, i.e. error due to wrongly predicted timing of changes, are far more problematic than level errors. Phase errors are usually caused by changes in wind speed or timing of weather front on large geographical areas which could lead to substantial forecast errors. (Holttinen et al., 2013)

In addition to level or phase errors, there is a systematic error imposed to the power system of just systematically variable production or load. The systematic error is frequently related to the load swings or solar power production changes. The problem is, that even if the timing and level of these two variables is known, there is still imbalance imposed to power system. Let us consider power consumption in Finnish power system on January 16th 2018, where consumption at 5.00 was 11 370 MW and in 8.00 it was 12 750 MW. In four hours, there has occurred an increase of demand by approximately 345 MW/h gradient. There is however little error in demand forecast. The forecasts are done based on consumption metered data, giving accurate results and timing of the demand increase is easily predictable by historical data. It can be thus said, that market knows exactly the behaviour of consumption pattern. However, the imbalance is nevertheless imposed, as even though the gradient of increase is known exactly, only the hourly averages are sold on the market. This obliges counterparties, the sellers and buyers, to comply only with hourly production volumes, neglecting the precise gradient of consumption. However, there could be a counter argument, that as long as the production increases with the same gradient as consumption, the imbalances will be balanced in organic way. There is no guarantee to that however, as the hourly granularity does inform the gradient of tradable asset to the counterparty. If 345 MW/h is traded, the consumption might have upward trend while production used to satisfy some of the demand might have downward trend, such can be the case with wind power. This causes an imbalance. The same thing applies to solar power. The timing of solar power production is more or less known, as it is caused by sunrise and sunset. Solar power producers know that their generation will increase in the morning and decrease in the evening. There is thus no phase error for solar power. Unfortunately, producers just cannot inform the increase to the rest of the market. Let us assume a situation, where it is known that solar power will increase on summer morning by 100 MW/h. The solar power producer sells 50 MW/h on the market. The counterparty that buys it, does not know the gradient of production. One could not tell if at the beginning of the hour the production would be 0 MW and at the end 100 MW resulting in 50 MWh of energy. The same amount of energy can be a result of a different gradient as well, say 40 MW and 60 MW during the beginning and the end of the hour respectively. If the gradients of production and consumption at BRP level do not match, it will result in imbalance of the system.

There is thus a common characteristic causing systematic errors to power system. Both solar producers and consumers know their gradient of production/consumption precisely, they have no mechanism to inform about it to the market. In other words, the forecasted pattern is spot on accurate, but it cannot be informed as day-ahead has too gross granularity. The hourly ISP is too big of a granularity for say consumers to follow the fluctuations of the renewables and react to them. These systematic errors leave TSOs in unfortunate situations, where TSO buy up-regulation in the beginning of the hour and buy down-regulation it in the end of the hour. The situation might be vice versa depending on the gradient of the variable.

Let us consider an event, like for example on 21th of January 2019, where in Finland day-ahead wind prognosis predicted wind power production increase from 180 MWh/h to 320 MWh/h on hours 11:00 -17:00. The continuously updated forecast predicted increase from 260 MWh/h to 600 MWh/h for the same hours. The actualized wind power production was 290 MWh/h to 820 MWh/h for the same hours, resulting in a level error compared to day-ahead forecast. The continuously updating forecast gives market participants time to react to the changes in intraday market, but there is still a large level error of wind power produced compared to the continuous forecast.(Fingrid Oyj, 2017)

The intraday market is not very liquid in Nordic countries, which results in a situation, that even if all the unpredicted electricity between day-ahead forecast and continuous forecast gets sold, it might be valued incorrectly as compared to day-ahead valuation. This is because very little fraction of demand is in the intraday market, which essentially leaves electricity to be traded between power producers, thus resulting in different market outcomes. The research by (Holttinen et al., 2013, p. 14) argues, that as forecast errors are penalized only about 50 % of the time, making wind power producers rather choose the imbalance settlement rather than intraday trading. Anyway, it seems that in these cases, wind power producers must either trade in low liquidity market or choose balance settlement, thus outsourcing system balancing to the TSO.

5 Impact of 15-minute ISP to the market

It is difficult to state at the time thesis was written how the ACER algorithm methodology will be implemented. Even if day-ahead coupling as it works today will move to 15-minute resolution, electricity is traded at best 12 h before the first quarter of delivery. This is somewhat long time for accurate prediction of power demand/supply for such a small granularity as a quarter. Furthermore, if day-ahead auction will go to 15-minute resolution cross border, it will occur earliest on August 2022, whilst 15-mintue ISP will be implemented one year prior to that. It can be therefore assumed, that at least for the near future after 15-minute ISP implementation, the most liquidity is in Day-Ahead auction on hourly products. However, the settlement occurs on 15-minute resolution, thus there arises a contradiction, how are hourly trades settled. For purposes of quarter hourly imbalance settlement, the volume of hourly trades made in day-ahead will be divided per each quarter (Energiavirasto, 2018). Say, if 1000 MWh is traded per hour, it will be noted in the balance as 250 MWh per each quarter. However, merely dividing the hourly scheduled position evenly per quarter does not bring any benefit of 15-minute ISP, since market liquidity is not in quarter hourly resolution. Changing ISP to 15-minutes allows settlement provider to settle realized production / consumption in smaller increments. It thus makes possible fining the market participants for sub-hourly imbalances against scheduled position. The very problem lies in scheduled position being allocated over the whole hour, forcing market participants to commit to the position also during quarters. In essence, nothing will change to hourly ISP. Thus, to get full benefit of 15-minute ISP, there should be a market place for market participants to fix their quarter hourly position to correspond to their actual production or consumption in order to avoid imbalance fees. Therefore, after implementation of 15-minute ISP in one way or another, BRPs should be able to fix their quarterly position, to escape imbalance fees. The only market place that would suffice needs of BRPs to fix their position is intraday. In the Nordics, this is not straight forward however, as there are concerns with liquidity.

As previously discussed in chapter 2.2, efficient functioning of continuous intraday market needs liquidity. A large pool of orders is needed for intraday to be efficient marketplace. At the moment, in the Nordics, there is only continuous intraday market. In 2018, Nord Pool’s Nordic and Baltic intraday market achieved all time high traded volumes with 8.3 TWh traded. The day-ahead market volume for the same region in 2017 was 396 TWh (Nord Pool Group, 2018). According to ACER market monitoring report, in 2018 the Nordic and Baltic intraday traded volumes accounted for only 1.8% of total demand, one of the poorest figures in whole Europe (C. ACER, 2018). Based on these figures, intraday liquidity is negligible compared to day-ahead liquidity in the Nordics. The possible explanation could be that all electricity demand is satisfied in the Day-Ahead market. In intraday, there is little demand for electricity, thus historically the market place could have been a place for producers trade with each other to fine-tune their positions. Furthermore, as continuous intraday market will move to quarter hourly resolution, there will be four times more contracts. Presumably, the intraday liquidity will be even smaller on quarters, as already existing liquidity needs to be divided to even smaller granularity.

Another problem with continuous intraday market is, that it does not establish a reference price on quarters. In this context the reference price is referred to as liquid market clearing price per product with availability of cross-border capacities. For instance, day-ahead price acts as a reference price for today’s hourly intraday trading. It is essentially the price around which the trading in intraday revolves, as all market participants have fixed their positions with that price in day-ahead market. Then again, just taking an hourly price and replicating it to the quarters is not a valid method to price the quarters, as each quarter may have combination of different cross zonal capacities, demand or RES production. Moreover, continuous intraday market does not value capacity, as discussed before. This is not necessarily problem for market participants, however, the closer the time of trading is to delivery hour, the higher the chance that capacity will be used. In other words, in intraday market there is always uncertainty, that capacity will run out from exporting market area, suddenly increasing prices in importing area by some margin. As already discussed in chapter 2, already realized trades in such case may not necessarily be the most socially beneficial. This dilemma becomes particularly evident when power retailer or industrial customers are concerned, as parties on demand side, want to subject their purchase of power to competition. If there is no cross zonal capacity, the less liquidity, the less competition.

At the same time, after introducing 15-minute ISP consumption metering will at least for the most part move to 15-minute resolution as well. According to article (Arora and Taylor, 2016) smart meters give valuable information about retail consumers demand patterns. These patterns can be further used to forecast electricity demand of retail customers. The higher the accuracy of the forecast the less error there is to procure the correct amount of electricity. As can be seen from eSett handbook (eSett Oy, 2015, chap. 7), consumption imbalance fees are higher than production imbalance adding an extra 7.5€/MWh on top of balancing market price. As the imbalance fines are high, it is highly doubtful, that electricity retailers would not use the quarter hourly resolution meter data in their forecasts. Thus, it can be presumed according to (Arora and Taylor, 2016), that accurate forecasting will transfer trading behaviour of market participants towards fixing position on quarters. According to this logic, electricity demand for some part would shift towards intraday, as it is the only marketplace holding 15-minute products, given day-ahead will remain on hourly resolution. This means more liquidity in the intraday, but for reasons such as optimized clearing and aggregated volumes the liquidity might shift to intraday auctions.

5.1 Intraday auction liquidity

There are various countries that have implemented intraday auctions across the Europe, Spain, Ireland, Italy, Germany and Great Britain. However, few of them have implemented quarter hourly ISPs as well. Of above mentioned countries, only Germany and Italy have quarter hourly ISP, whereas Italy has 15-minute ISP for production and 60 minute ISP for consumption.(Frontier Economics, 2016) Analysing the market structure of Germany gives and insight how market has developed to cope with quarter hourly ISP. First of all it is important to note, that Germany has substantial amount of VRES installed in the power system, namely 45GW of wind power and 39 GW of solar photovoltaics (Gürtler and Paulsen, 2018). Therefore, quick ramping of generation occurs frequently in Germany and with high amplitudes. The day-ahead auction in Germany is still hourly and holds the most liquidity. This is the expected market structure for the Nordics after implementation 15-minute ISP. Just as discussed in previous chapter, there should be some market where market participants can balance their positions on 15-minute resolution. For those reasons market participants would choose a market with 15-minute contracts available to trade. The analysis is subjected to German 15-minute intraday auction run by EPEX SPOT, which is auction that is expected to be the place for market participants to balance position after day-ahead auction. The 15-minute auction, sometimes in scientific literature referred to as Call auction, is held at 15:00 CET d-1, 3 hours after day-ahead gate closure (Epex Spot, 2019a).

The assumption is that liquidity is brought to intraday auction for market participants being able to fix their quarter hourly position. The causation that leads to such shift of liquidity is explained in figure below.

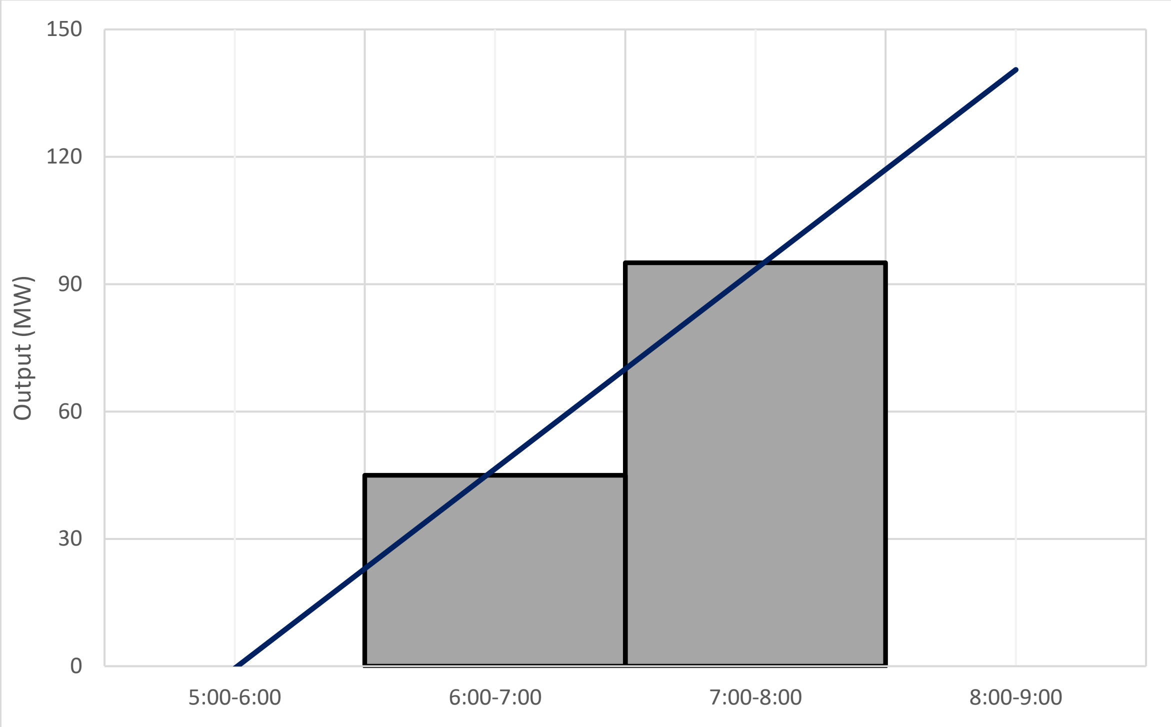

Figure 6: Illustration of actual production versus scheduled production after Day-Ahead market

The blue trend line in Figure 6 can depict one of three major variables unknown to market, the wind production profile, the load profile or the solar production profile before day-ahead gate closure. At this point any of those three are forecasted profiles, as the trading occurs day-ahead. For this illustration wind production profile can be considered. The grey columns represent the amount of electricity traded (sold) in day-ahead market by market participant with respect to wind power output prognosis. The first hour is expected to produce total of 45 MWh and second hour is expected to produce 95 MWh. However, as there is 15-minute ISP, although electricity is traded hourly, the hourly traded volume is distributed over the consecutive quarters, as depicted in figure below.

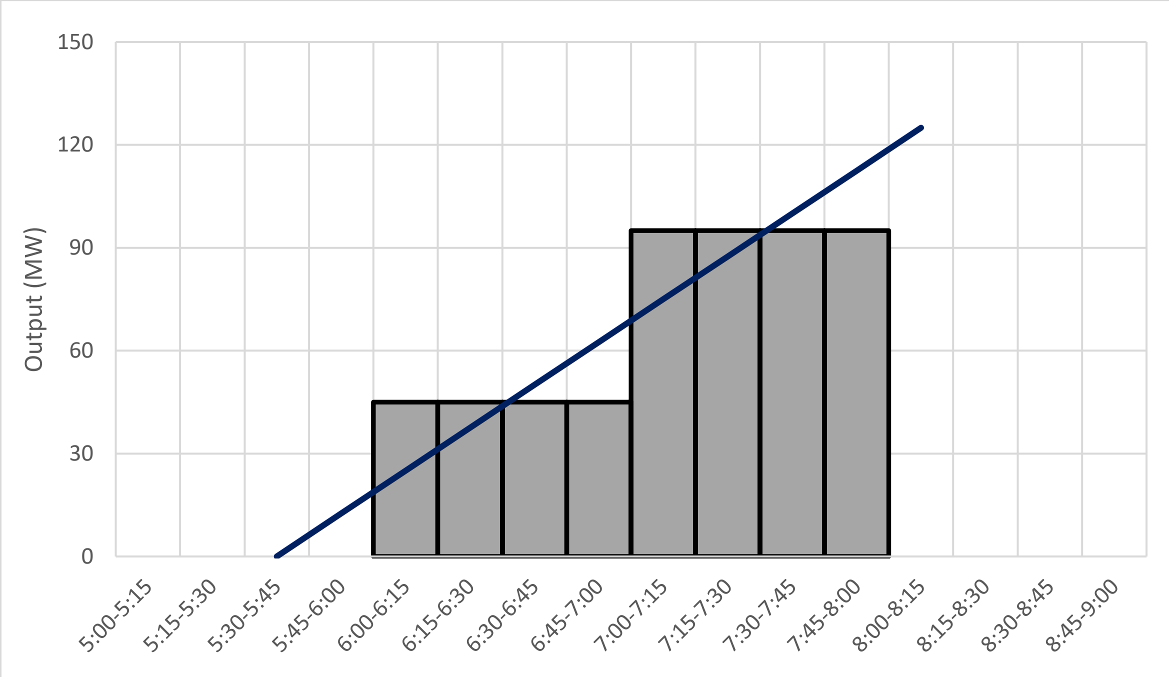

Figure 7: Illustration of actual production and distribution of scheduled production on quarters in 15-minute ISP

In figure 7 the dark blue trend line is the same trend line as in figure 6. The difference is that hourly volumes are distributed over the quarters. Now there can be clearly seen that volume for individual quarters has been inaccurately allocated with respect to forecasted production. Therefore, for market participant to remain in balance within quarter hourly ISP, one must buy big chunk of electricity during first quarter, buy smaller amount of electricity at second quarter, sell small amount of electricity during third quarter and sell large chunk of electricity during last quarter of the hour. However, on the first quarter of next hour market participant should again buy electricity. Thus, there occurs repetitive behaviour for market participant with respect to the portfolio trend during consecutive hours.

It is important to understand the scale of such repetitive behaviour in the market. Renewable power generation is dependent on weather patterns which usually affect large geographical areas. If there is such situation that market participant's power production rapidly rises, it is most likely the case for many other wind power producers as well. When the whole German market is considered, even if not all wind power is sold to the market or the favourable weather conditions apply only to some parts of Germany, such repetitive, or directional, behaviour is still of substantial size. The figure 7 is just an illustration, in real life the demand profile or wind production profile would not be linear. By the directional behaviour in this case is meant that variable profile is clearly increasing or clearly decreasing, leading to situation that during each hour both buying and selling needs to occur in order to balance position of BRP. As this type of systematic, cyclical, trading behaviour occurs in discrete auction, it should be visible in auction prices as well. The hypothesis is, that there should be clear, visible patterns of quarter prices within an hour. The price level will most likely reset during next hour and follow the same pattern. The patterns or quarter hourly prices will change during the day, as directional behaviour of production or consumption goes systematically both ways during the same day.

To test this, this thesis analyses price data of 15-minute German intraday auction during 2018 compared to German day-ahead price data for the same time frame. Both auctions were run by power exchange EPEX SPOT. Prices for each quarter of year 2018 from 15-minute call auction as well as all 8760 hours from day-ahead auction are considered for this analysis. In order to find out if there is any directional behaviour in the data such as theory predicts, the average of contract prices is taken. The electricity price data is very cyclical; daily, weekly and seasonal cycles apply for the data. In order not to generalize the data and look over the seasonal cycles a small enough timeframe needs to be chosen for analysis. Then again, the timeframe cannot be too short in order not to include statistical anomaly. The chosen timeframe for analysis of the data is one month. This timeframe is believed to find patterns in the data from decent number of contracts, but not to average the seasonal cycles. The monthly mean price for each contract has been calculated and displayed as daily profile. Therefore, for each price point the mean number of contracts is n=29, 30 or 31 depending by calendar month. When such profile is constructed it essentially shows the average day in a month. The figure below is shows means contract prices of December 2018.

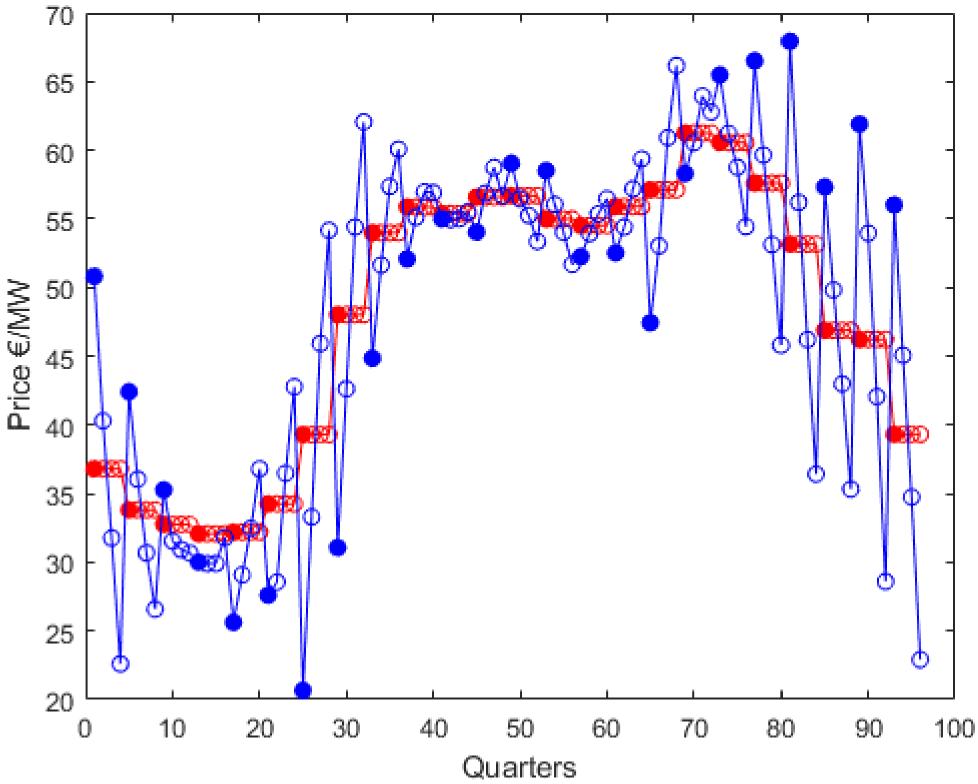

Figure 8: EPEX intraday quarter hourly call auction prices compared to day-ahead prices of December 2018. Blue circles represent intraday auction prices on quarters, red circles represent hourly day-ahead prices. Filled circles represent beginning of the hour.

The Figure 8 contains a blue line and red line. Blue line represents intraday auction prices, with circles indicating specific price per each quarter. Red line represents day-ahead price, with four circles in a row as hourly price is divided per four quarters. With such arrangement each quarter hourly price can be separately compared between intraday and day-ahead. The x-axis displays quarters in a day, of total 96 quarters. The filled circles ease noting start of each hour, but also help understanding the price behaviour of quarters around the day-ahead price. The first observation that can be done from the figure is that intraday price is generally more volatile than day-ahead price. The average lowest and highest price in the December for intraday market is 20.7 € and 67.9 € respectively. For day-ahead the figures are 32.1 € and 53.8 €. Therefore, the intraday auction market can be considered more volatile. Another important observation from the figure is that each hour the price in intraday auction generally develops in certain direction. What is more remarkable, the directional pattern is replicated hourly, revealing so called zig-zag pattern. The repetitive price pattern suggests a cyclicity of intraday auction price. In order to further analyse the data, the interval of cyclicity needs to be found. For this the matlab function of find peaks is used.

```
[pks,locs] = findpeaks(data)                                      (5)
```

`pks = findpeaks(data)` returns a vector with the local maxima (peaks) of the input signal vector, data. A *local peak* is a data sample that is either larger than its two adjacent samples or is equal to Inf. Whereas `locs` finds the location of the `pks`.

```
Y = diff(X)                                                       (6)
```

`Y = diff(X)` calculates differences between adjacent elements of X along the first array dimension whose size does not equal 1. The matlab is asked to perform following calculation:

```
cycles = diff(locs);
meanCycle = mean(cycles)
(Answer:)meanCycle = 4
```

The command above calculated differences between adjacent locations of peaks. This gives a difference of locations, in this case number of quarters between peaks. The mean cycle of those locations is calculated, the answer being 4. This means that intraday prices peak every 4 quarters of average, meaning data is cyclical with respect to hourly cycles. The fact that intraday price data is cyclical around hourly cycles suggests that it is cyclical around day-ahead timeframe and presumably the day-ahead market. It is very logical that intraday auction follows hourly timeframe, as most of liquidity is on hourly contracts in day-ahead. What needs to be examined, is whether intraday auction prices follow the day-ahead prices. If intraday auction prices follow the day-ahead prices, it suggests, that intraday quarter hourly auction is complimentary auction to day-ahead auction. If the prices of intraday auction are not following the day-ahead prices, it means that intraday auction is a separate, independent, quarter hourly market. One way to test this, is to compare the average prices of day-ahead auction and intraday auction.

Table 1: Monthly average day-ahead and intraday call auction prices from 2018 and their difference

	DA_averages	IDA_averages	Delta (DA-IDA)
December	48.13	47.69	0.44
November	56.30	56.45	-0.15
October	53.02	52.43	0.58
September	55.59	54.82	0.77
August	55.93	55.76	0.16
July	49.04	49.17	-0.13
June	42.48	42.23	0.25
May	32.60	31.95	0.64
April	32.41	31.40	1.02
March	37.82	37.99	-0.17
February	39.81	40.02	-0.21
January	29.47	29.10	0.36

Table 1 shows monthly average prices of day-ahead and intraday markets. The third column shows monthly differences between day-ahead and intraday mean monthly prices. It can be seen from the third column, that the average prices are systematically close to each other. The highest monthly average difference is 1.02 € in April. From the results of the table can be seen that both hourly and quarter hourly markets value electricity somewhat equally. Thus, the resolution of a market does not have significant impact on the daily price of electricity. The result can be justified, as intraday call auction occurs 3 hours after day-ahead market for the next day and little new information has reached market participants to have effect on trading behaviour, thus the prices. Nevertheless, the result is somewhat peculiar, as intraday auction has significantly smaller liquidity than day-ahead auction and is not subjected to any form of market coupling. The average prices are nonetheless very close to day-ahead prices, and systematically follow the monthly price level changes of day-ahead market. This heavily suggests, that intraday call auction is complimentary market to day-ahead auction. This assumption supports the hypothesis. To follow the assumption, the price dynamics of intraday quarterly market needs to be examined against day-ahead market prices.

Given that average quarter hourly auction prices do not deviate from average day-ahead prices does not yet tell that the prices are dependent. There is a possibility that two separate markets systematically arrive to the same outcome. However, given that quarter hourly auction prices have local maxima's and local minima's every hour on average, not affecting the daily average price, suggests heavily that intraday auction price follows day-ahead price pattern. This is visible from figure 9, as monthly average day ahead price is for the most part between hourly local maxima and local minima of monthly average quarter hourly prices. In order to find out the dependency between price patterns of day-ahead auction and intraday auction the location of quarter hourly price peaks need to be analysed, and check whether those correspond with the hypothesis. The figure below is used to clarify this.

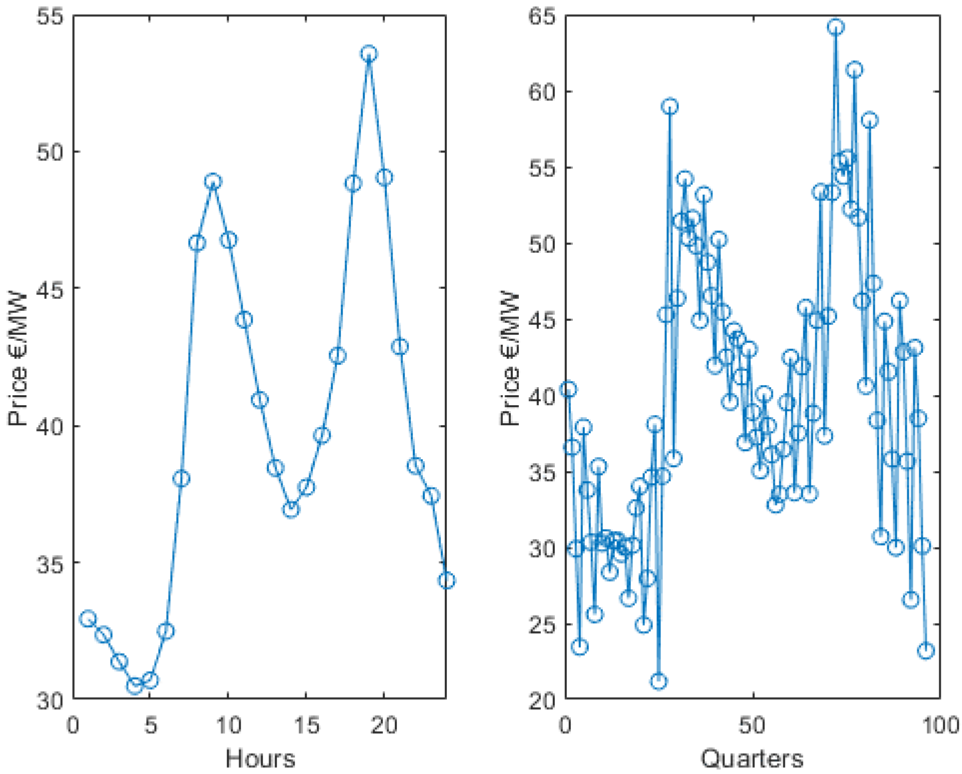

Figure 9: Day-Ahead and Intraday auction monthly average price profiles of February 2018. Circles in left figure represent hourly prices and circles in right figure represent quarter hourly prices.

In figure 9 there are two price figures, the first one is average day-ahead daily profile from February 2018 and the second one is average daily intraday call auction profile from February 2018. By average daily profile is meant, that each price point in a figure represents average of all prices of current contracts within a month. Thus, when all contracts are considered average daily profile of a month is formed. The figure with 24 contracts is from day-ahead market, the right one and figure with 96 contracts is from intraday call auction, the left one. The figures look similar, but what is worth noting is the shape of the day-ahead graph. As the graphs are averages for one month, the price patterns are quite systematic. First, there is moderate decrease of price during first four hours, followed by rapid increase of price during the morning hours. The price then rapidly drops, followed by sharp spike, i.e. rapid increase and following drop. The intraday auction price pattern is reminiscent to day-ahead price pattern. In the next figure the two price patterns are made to overlap, showing essentially the same figure as figure 8 before, just for February.

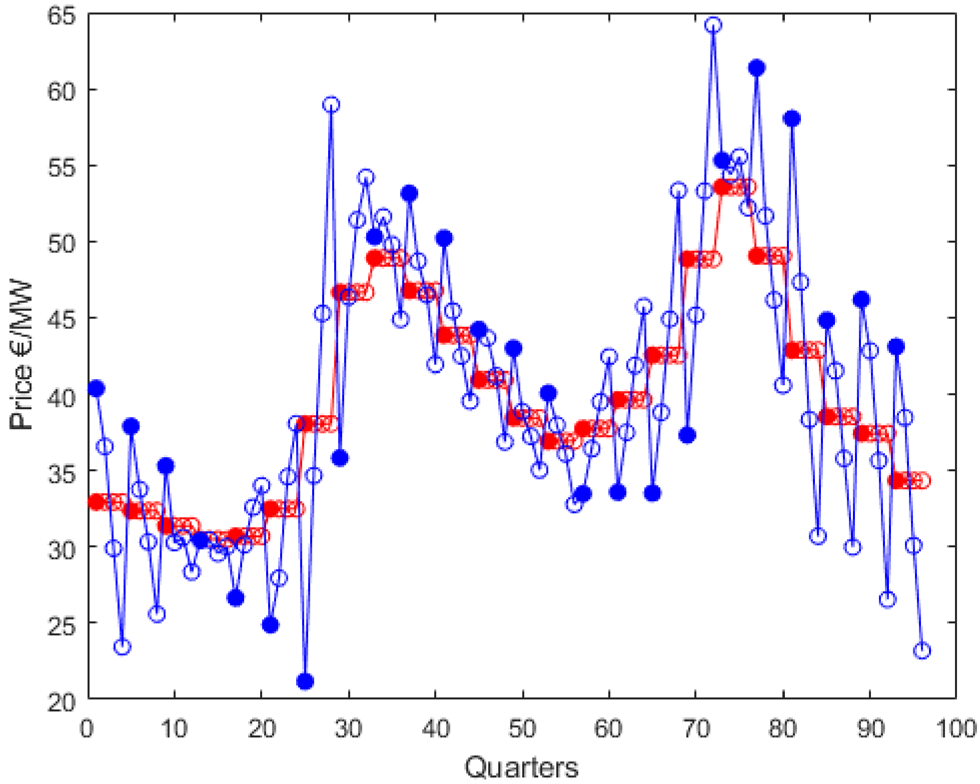

Figure 10: EPEX intraday quarter hourly call auction prices compared to day-ahead prices of February 2018. Blue circles represent intraday auction prices on quarters, red circles represent hourly day-ahead prices. Filled circles represent beginning of the hour.

In Figure 10, the blue line depicts monthly average intraday call auction prices whereas the red line depicts monthly average day-ahead prices. The filled data points represent beginning of each hour. Let us analyse how intraday price peaks align with day-ahead price and whether there is any consistency. The remarkable observation is, that when day ahead prices decrease, the price peak of intraday call auction is always on the first quarter of an hour, whereas when the day-ahead prices increase the price peak of quarter hourly auction is always on the last quarter of an hour. During the first four hours, when day-ahead prices decline, the peak prices of quarter hourly auction are on first quarters. When day-ahead prices begin the rapid increase, the peak prices of intraday auction are on last quarters. When the day-ahead price peak during the day starts descent, the intraday auction hourly price peaks are again during first quarter. The same behaviour is clearly visible for the next peak as well. The peak hourly prices of intraday auction (local maxima's) occur only during the first or last quarter, with precisely 3 exceptions, which are the pivoting points, when day-ahead price increase turns into decrease. The exceptions occur during hour 4, 9 and 19, which are precisely the day-ahead local minima, local maxima1 and local maxima2 respectively.

There thus can be clearly seen differences between price patterns of day-ahead and intraday auction. From Figure 10 it can be seen, that intraday auction price follows price pattern of day-ahead market price in very structured manned. It is also more volatile around it on hourly cycles. This can be explained by too large contract resolution of day-ahead market to satisfy market participants positions on 15-minute ISP. Day-ahead gives a uniform market price for each quarter within an hour. Also, the day-ahead price experiences daily fluctuations due to phenomena's which occur linearly over time, not in hourly increments. Therefore, the layered or stepwise hourly pricing in day-ahead auction creates a systematic error in pricing the electricity, just like discussed in hypothesis. According to findings presented above, the intraday auction tends to correct the pricing error of day-ahead market. This explains the positioning of quarter hourly peaks in intraday auction data against day-ahead price. When day-ahead price rapidly increases as is observable from Figure 10, the quarter hourly prices indicate, that the first quarter of the day-ahead contract is overpriced, whereas last quarter of day-ahead contract is underpriced. The quarter hourly prices in the intraday auction are therefore low for first quarter and high for the last quarter. The price pattern is vice versa when day-ahead price is declining, where first quarter is underpriced, and last quarter overpriced. Therefore, the intraday auction pattern is very structured. Based on these observations it can be said that intraday auction is a complimentary market to day-ahead market.

In order to properly understand the nature of zig-zag pattern of quarter hourly intraday call auction prices, the amplitude of fluctuations of quarter hourly prices in intraday call auction need to be analysed. When analysing intraday auction fluctuations, it is important to note, that day-ahead price also fluctuates. The day-ahead price just like any auction price is determined by intersection point of demand and supply; the volumes offered by market participants. If price fluctuates, it means that intersection point between demand and supply moves on the price scale up or down. Therefore, price fluctuations are result of changes in demanded volume against supplied volume. The factors that cause the fluctuation of price in day-ahead on short term, are the same factors which force market participants to fix their position on quarter hourly resolution; the fluctuation in demand and variable renewable energy sources (VRES). In other words, it is the same phenomenon that causes fluctuations of price in day-ahead and zig-zag pattern in intraday call auction.

The “zig-zag” pattern reflects volatility of intraday auction. It is volatility of intraday-auction prices. The price volatility was predicted in the hypothesis and explained by error in allocated volume against actual volume of VRES or demand. If this is so, the intraday call auction price volatility should increase hand in hand with day-ahead price volatility. This is based on logic, that if day-ahead price rapidly increases, there is swift change of circumstances in supply-demand curve, given that market is liquid and not manipulated. For example, in the morning the day-ahead price might rapidly increase due to rapidly increasing demand whereas during the day prices might decrease due to flood of solar power to the market. It is not concern of this thesis what factors exactly drive the electricity prices in any direction and thus cause volatility. Given that volatility in electricity market occurs, some of variable factors as VRES production or demand swings are dominant and cause volatility both in intraday and in day-ahead. Thus, the hypothesis is that the higher the price swings in day-ahead price the higher the price swings in intraday price around the hour. This is because, the higher price changes in day-ahead, the more there is error in allocated volumes in day-ahead and thus the more there is to correct on quarters in intraday-auction. This should be seen in the data.

As the day-ahead data shown for example in figure 9, is a compiled average of contracts during the month, it is difficult to analyse volatility of such short sample. In order to properly compare volatility between day-ahead market and intraday market both datasets should be analysed as strings, however the strings would have different length thus making the analysis difficult. Therefore, the data representation will stick to the same depiction as before, in this case the volatility of day-ahead price is basically the price increase or decrease. In the figure 11 below there is presented average day-ahead profiles of January 2018 and August 2018.

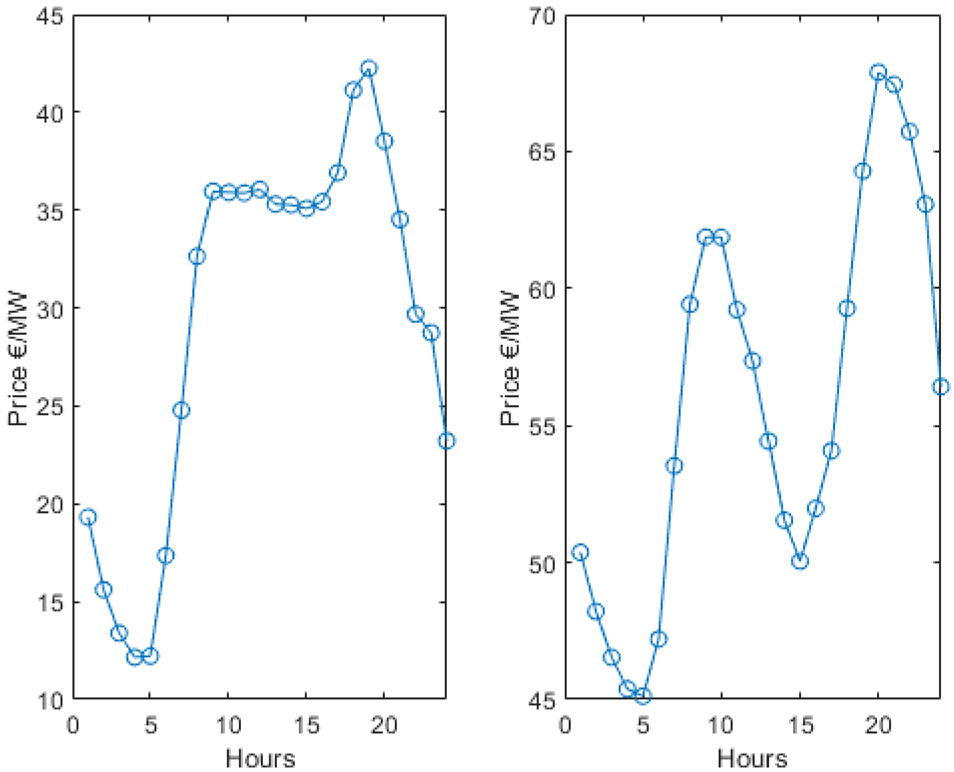

Figure 11: Day-Ahead monthy average prices in January and August 2018. Circles in left figure represent hourly prices and circles in right figure represent quarter hourly prices.

In the figure 11 above can be seen daily average profiles of January 2018 (the left graph) and of August 2018 (the right graph). Just as in earlier figures, each dot represents an average price of an hourly contract during the whole month. It can be seen from the figure that the daily profiles are different between these two months. They both start with decreasing price pattern during first 5 hours, after which starts rapid increase in prices. After the morning peak happens the differential part. In January (the left graph) prices remain stable for 8 hours or so after experiencing evening peak followed by decrease of prices. In August (the right graph) the prices undergo sharp decline before the evening peak and consecutive decrease in prices. In august the day-ahead prices experience more fluctuation, i.e. up and down movement. However, the morning peak is sharper in January's prices, but evening peak is sharper in August's prices. It is also important to note, that January and August prices are on different price scale in figure 11.

The figures below display the intraday auction volatility of the same months which' day-ahead price pattern was depicted in figure 11 above. At this point it is important to understand, that volatility in this case means what pattern the prices take within a day. By volatility is not meant the volatility of single price point during the period of analysis.

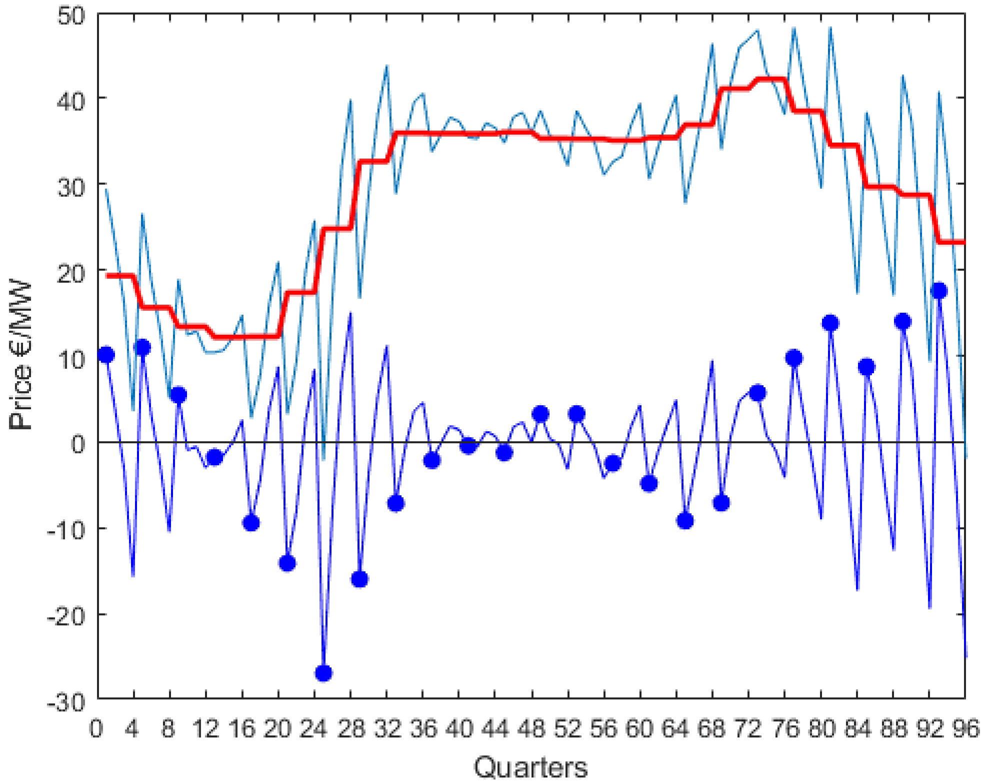

Figure 12: Volatility of Intraday call auction prices against day-ahead prices in January 2018. Thick red line represents day-ahead price, violet line represents intraday auction price. 0-axis line represents day-ahead price, while blue trandline revolves around it. Filled circles represent beginning of the hour.

Figure 12 above shows volatility of intraday auction prices in January 2018. The thick red line represents hourly day-ahead prices, with each hour extended to four quarters. The violet line represents intraday-auction, revolving around the day-ahead prices. The blue line represents intraday-auction prices with average component removed. In other words, blue line is obtained from subtracting day-ahead price from intraday price. The day-ahead price is now the 0-axis and blue line of intraday price revolves around in. The intraday data just like day-ahead data is monthly average from January. The filled blue dots represent the first quarter of each hour. From the blue line the volatility of intraday auction can be relatively easily seen, as intraday auction price fluctuates around fixed axis.

It can be seen from the figure 10, that intraday auction price volatility follows the day-ahead price fluctuations. When there is decrease of day-ahead prices during first hours of the day, the fluctuation of quarter hourly prices is between 10€ and -10€ which then decreases when day-ahead price reaches local minima. When rapid increase of day-ahead prices occurs during morning peak the volatility of intraday auction fluctuations increase dramatically. When day-ahead price starts mid-day plateau phase, the volatility of quarter hourly price decrease significantly, nearly to inexistent. However, when day-ahead price reaches evening peak, the volatility somewhat increases, but it increases even more so when drastic drop of day-ahead prices is seen. For the comparison figure below depicts intraday auction price fluctuation of August, where day-ahead price only moves steeply up or down without any plateau phase, as visible from figure 11.

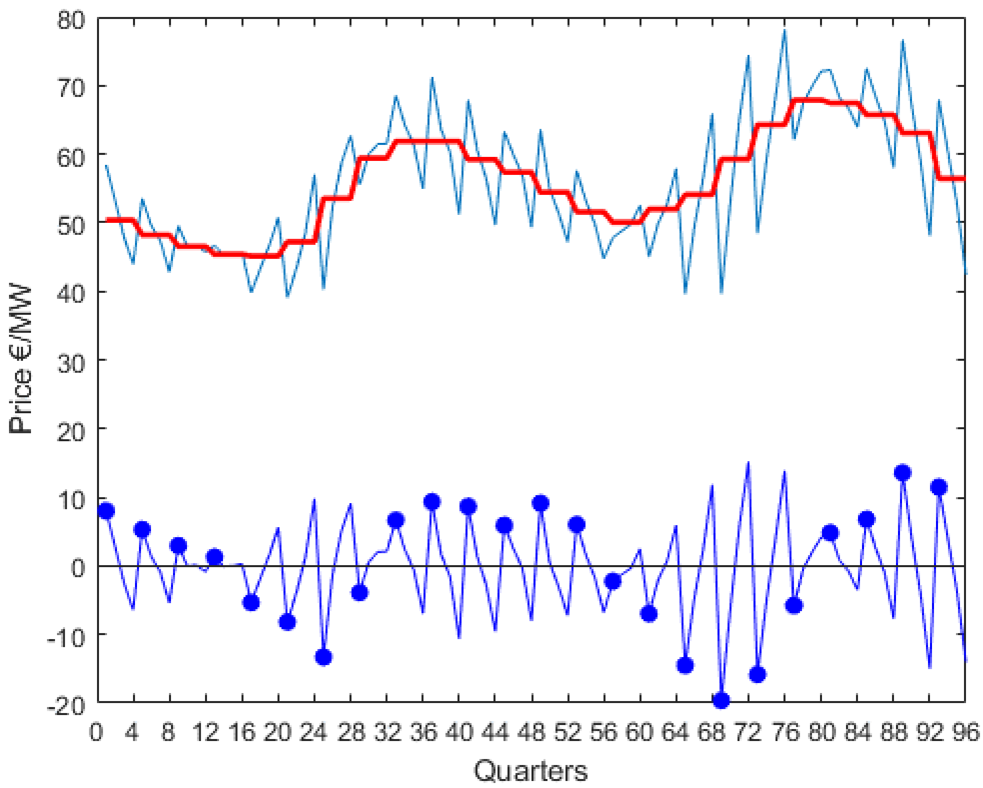

Figure 13: Volatility of Intraday call auction prices against day-ahead prices in August 2018. Thick red line represents day-ahead price, violet line represents intraday auction price. 0-axis line represents day-ahead price, while blue trandline revolves around it. Filled circles represent beginning of the hour.

The figure setup of Figure 13 is the same as in Figure 12. The colours of the lines are the same and the lines depict same prices as in Figure 12. From Figure 13 it can be seen that volatility of quarter hourly prices is somewhat constant. The only occurrences when volatility of intraday auction prices is low is when the day-ahead price curve changes the direction, i.e. hits the local maxima or local minima. The exception to this is when day-ahead price reaches local maxima, the first peak of the day, the intraday auction prices are volatile. Essentially the decrease of volatility has happened prematurely an hour before the peak, on hour 8. Based on this observation, volatility, that is amplitude of peaks and crests of intraday auction prices correlates with slope of the day-ahead price. As day-ahead price is constantly changing in August the volatility remains constant, as it should, because the pricing error of day-ahead is uniform around the day on average.

When comparing the Figure 10 and Figure 11 together, there arises a question, why does volatility of intraday auction prices reach higher amplitudes in January during day-ahead price increases and decreases compared to August. There might be several explanations to this, however also in this case the slope of day-ahead prices can be addressed. In January day-ahead price increased on average 24€ during hours 5.00 AM to 10.00 AM. In August during the same hours the prices increased on average 17 €. As morning price peak in January went through quicker increase in prices, the intraday auction volatility is higher as well than compared to August. There can be seasonal components that affect the intraday auction price volatility as well as price levels could affect the volatility as price can have different elasticity at different price levels. However, it can be seen form the data of figures 12 and 13, that intraday auction volatility tends to correlate with steepness of day-ahead price curve, rather than with price level of day-ahead market. Generally, the quarter hourly price volatility follows the day-ahead price fluctuations. The more there is Day-ahead pricing error to correct the higher the intraday auction price fluctuations and vice versa. This is in line with hypothesis.

As volatility of intraday auctions is considered from monthly contract averages, it is very important to analyse the standard deviation of the prices as well. When average of prices is taken over a period of time, only the systematic part is depicted, it is important to pay attention to deviations as well. There is a peculiar observation, that standard deviation of monthly quarter hourly prices also follows the cyclical pattern as can be seen from Figure 14 below.

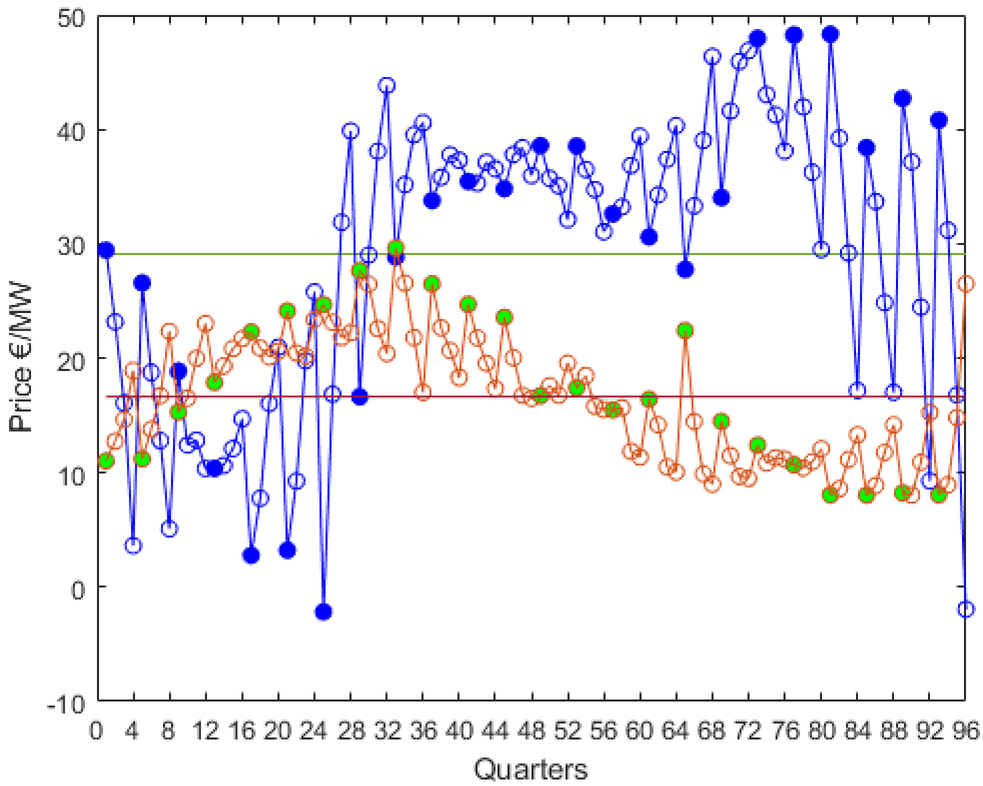

Figure 14: Standard deviations of respective quarter hourly contract prices of January 2018. Blue circles represent intraday auction prices on quarters, green circles represent the standard deviations of respective prices. Filled circles represent beginning of the hour. Upper y-axis line represents monthly average price, lower y-axis line represents monthly average standard deviation.

Figure 14 has two trendlines, blue and green. The blue trendline depicts a monthly average of intraday call auction prices from January 2018. The green trendline depicts standard deviation for each respective intraday auction contract price. Every filled circle is the first quarter of an hour thus signifying the beginning of each hour. There are also two flat lines in the figure, the upper flat line is the average price of 15-minute intraday auction in January 2018 and lower line is average standard deviation of prices in January 2018. First observation from the figure is that standard deviation on average is quite high. The average prices are around 30€/MWh and average standard deviation is around 20 €/MW, thus about 60 % to 70 % of the average price. For some specific contracts, the standard deviation is even higher than the average price itself, signifying very volatile prices of intraday auctions. It is visible from figure, that standard deviation in intraday auction contract prices follows the same cyclical pattern as the intraday auction prices themselves.

This is a very peculiar finding. The cyclicity of intraday call auction prices was explained by dependency from day-ahead prices. The cyclicity of standard deviation is difficult to explain by day-ahead trading. When the same set of commands in MATLAB is performed as introduced previously, the mean cycle of peaks for standard deviation is 3.8, which means that the peaks do not strictly follow the day-ahead timeframe, however the cyclicity is evident. When analysing the relation of intraday quarter hourly price peaks to standard deviation peaks, an interesting pattern is found, when intraday prices reach local maxima, usually the standard deviation reach local minima, and vice versa. As it is known that intraday auction prices peak in very systematic manner every hour and, depending from direction of day-ahead price, the peak is either the first quarter or the last quarter makes the finding even more peculiar. Essentially it tells, that there is systematic behaviour of standard deviation for contracts within an hour. Very important finding is, that standard deviation is alternating, not constant. It is also found out, that standard deviation alternates within hourly timeframe, against the direction of intraday quarter hourly price, thus the day-ahead price as well. It is very difficult to find a causation for such behaviour; more research needs to be done on the topic to find conclusion. What can be said from the observation, is that generally when quarter hourly peaks, the so-called market forces tend to agree on the price, thus the standard deviation is lowest. It could be thought that high prices alternate in smaller range than low prices. When quarter hourly prices within an hour are low, the standard deviation tends to increase, which means, that market forces cannot agree how cheaply the electricity can be valued. This behaviour could stem from price elasticity of demand. Low intraday auction price usually means that a lot of electricity is sold, and as little demand reacts to change in price level, the prices can drop even to negative values. From the figure it can be found that prices are more volatile downwards, and less volatile upwards.

5.2 Previous literature

There has been previous research conducted on econometrics of intraday auctions by (Kiesel and Paraschiv, 2017). The research article had identified the same “zig-zag” pattern on intraday call auction prices. The baseline for explaining the zig-zag pattern has however been completely different than is this thesis. The article (Kiesel and Paraschiv, 2017) argues that zig-zag pattern occurs ultimately from updated forecasts of either renewables such as solar and wind or from demand. The article’s main assumption is that the electricity intraday price formation process depends on how much traditional capacity has been allocated in the day-ahead market and in which proportion it covers the forecasted demand (Kiesel and Paraschiv, 2017). Therefore, the intraday price behaves according to change of forecast compared to already allocated capacity in the day-ahead market. This thesis does not contradict with such assumption nor results. Forecasting errors will be discussed later in this thesis. However, there is clearly differential of interpretation of intraday zigzag pattern between these two studies.

The article has clearly identified the possible trading behaviour which would lead to such zig-zag pattern. In the Figure 3 of the article it is explained by systematic solar production ramp-up. Article argues that solar power producers sell hourly mean production quantity to day-ahead market, but as actual solar production is not in line with hourly day-ahead production schedule, market participants are forced to participate in intraday continuous market. As solar production is ascending in the morning, there is buy pressure in the first quarters of an hour and sell pressure on the last quarters of an hour. For the evening as sun descends, the buy-sell pressure is reversed. The zig-zag pattern therefore is descending in hourly cycles in the morning and ascending in hourly cycles in the evening.

This is where this thesis disagrees with the article with by (Kiesel and Paraschiv, 2017). The data for the article is said to be from 01/01/2014-01/07/2014. The data from 2018 used in this thesis for those months does not follow the patterns depicted in figure 3 of the article. This means, that the analysis is not reproducible. Even in the sunny months such as June and July the price pattern of intraday auction price is contradictory with the direction of peaks compared to the results of the article. This means, that explanation for zig-zag pattern provided by the article is not comprehensive. It could be, that intraday continuous zig-zag pattern analysed in article differs from intraday auction zig-zag pattern, but it is unlikely. Furthermore, the article has chosen only hours 8-19 of zig-zag pattern for the analysis explained by solar production, which takes away credibility of results, as the zig-zag pattern is visible over the whole 24 hours of a day. The article acknowledges that in figure 4, stating that such zig-zag pattern was observable also during the so-called off-peak hours 20.00-08.00. In the article, the zig-zag on off-peak hours (20.00-08.00) is explained by production design of fossil power plants or power-intensive industry. It is not however explicitly stated how is it explainable by fossil power plants or power-intensive industry. An important factor which is left uncovered in analysis by the article, is the connection between figure 3 and figure 4. Exactly at hours 19.00-20.00, where the figures 3 and 4 are split, the zig-zag pattern changes directions. This change of directions is not explained or referred in the analysis. According to figure 3 in the article, the sun is still shining at 19.00, therefore why would the direction of price pattern change, is left uncovered. To further enhance the differences between the article by (Kiesel and Paraschiv, 2017), no analysis on volatility nor on amplitude of the peaks has been concluded by the article. In the figure 3 the solar generation curve has been presented which is believed to cause the zig-zag behaviour. The during hours 8.00-13.00 the gradient of solar production is clearly steeper than during hours 13.00-16.00. In fact, the solar gradient is nearly flat during hours 13.00-16.00. The auction price is still nearly as volatile as it was during morning hours. According to article, the volatility of intraday auction prices should be clearly higher on morning hours than on mid-day, however this is not explained. There is thus a gap in research on comparison of intraday auction price peaks compared to day-ahead prices and on volatility analysis of intraday auction price peaks, which signify the struggle of day-ahead auction to value quarter hourly electricity correctly.

Generally, article explains the zigzag pattern by systematic behaviour of generation assets. I.e. solar generation has some sort of systematic behaviour; therefore, the intraday continuous price develops a complimentary way systematic behaviour. To some extent this thesis also agrees with this assumption. The article states that forecasting errors will put pressure on traditional suppliers to reduce production, since renewables are fed into the grid with priority. This thesis has different approach towards the phenomenon. This thesis believes that zig-zag pattern of intraday auction price is the correction of positions against day-ahead market due 15-mintue ISP. Therefore, this thesis considers 15-minute call auction to be of complementary nature to day-ahead auction. According to this thesis the price pattern of intraday auction will always follow day-ahead auction regardless of generation, demand, renewables, or any circumstances. Although this thesis has noted the same variables as the article, namely solar generation, wind generation and demand, it is never possible to explain the zigzag pattern by only one of these variables, as reality is always a combination of these three. Therefore, there has to be comprehensive approach to explain the price pattern of intraday-auction, and according to this thesis it is the complimentary nature to day-ahead auction.

The article has acknowledged the zig-zag behavior of intraday continuous prices and also found the cyclicity, however it does not analyze the amplitudes of intraday auction peaks neither does it run comparison of it against day-ahead market price.

5.3 Systematic pricing error of day-ahead auction

Up to this point it has been identified that intraday auction prices are cyclical around hourly day-ahead prices. The behavior of quarter hourly price peaks has been analyzed and found that direction of peaks is nearly always aligned with day-ahead price patterns. The phenomenon was explained by day-ahead granularity being too large and thus resulting in erroneous price on quarters for continuous variables such as VRES production and demand fluctuations. To test this the intraday auction price volatility was compared against day-ahead price fluctuations and found, although not explicitly, that intraday auction volatility generally follows day-ahead price fluctuations. The higher the day-ahead price fluctuation the higher the pricing error on quarters to adjust in intraday auction thus the higher volatility of intraday auction prices. It is all logical, however, there arises a question of why intraday auction prices fluctuate more within an hour than previous and next day-ahead hourly prices if intraday auction quarter hourly prices were only to fix the error of day-ahead price on quarters. The figure below illustrates the dilemma.

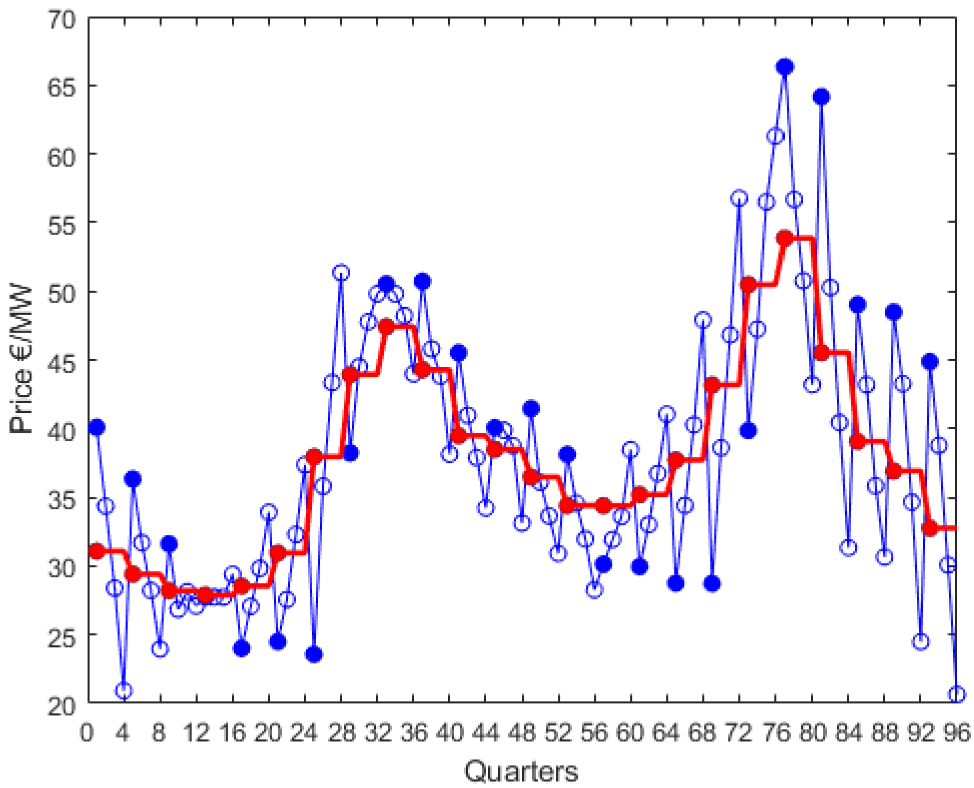

Figure 15: EPEX intraday quarter hourly call auction prices compared to day-ahead prices of March 2018. Blue circles represent intraday auction prices on quarters, red circles represent hourly day-ahead prices. Filled circles represent beginning of the hour.

The figure 12 above shows average day-ahead and average intraday prices on March 2018. Blue line depicts intraday call auction prices, each filled dot signifies first quarter hourly contract of an hour whereas dots with no fill signify the other contracts of an hour. The thick red line depicts day-ahead price, where filled red dots indicate the beginning of each hour. It can be seen from figure that intraday auction prices during certain hours range more than consecutive day-ahead prices. Let us take into consideration the evening day-ahead price peak, the second peak in the figure on hours 17.00-20.00, or on quarters 68-80. It can be seen that intraday auction prices are so volatile, that local peaks exceed the day-ahead price of next hours and hours after that. The explanation for intraday volatility was day-ahead pricing error on quarters. If intraday auction were to correct day-ahead pricing error on the quarters, why does it not happen within the boundary of adjacent hourly price limits set by day-ahead market. Let us go back to theory in figure 7. Let us consider that figure 7 reflects increasing demand of whole market and the analysis will be about pricing the situation in figure 7. Price on 1st quarter of first hour in figure 7 would be the cheapest, price on second quarter would be cheaper than day-ahead price third quarter would be more expensive than day-ahead price and fourth quarter would be more expensive than day-ahead price. The price of the first quarter of second hour should definitely be higher than day-ahead price of first hour. This is because day-ahead market has valued electricity based on the volumes. If first quarter of second hour would be cheaper than last quarter of first hour, it would mean, that consuming more electricity would cost less. Given that day-ahead market values electricity hourly, the valuation threshold of quarters will also be hourly, therefore the lowest price for first quarter of second hour should be at minimum the day-ahead price of previous hour. Under no circumstances, at least not systematically, should the intraday auction price go below the day-ahead price of previous hour. If we consider again figure 15, it is exactly what is happening. Is there a paradox, why does average prices of intraday auction follow day-ahead auction price hand in hand but quarter hourly prices do not respect the hourly valuation of electricity in day-ahead. The day-ahead market has significantly higher liquidity than intraday auction. Therefore, there is little ground to question hourly valuation of electricity on day-ahead. Tus, what most likely is happening, is that intraday quarter hourly auction actually does not value the price of energy. The theoretical considerations presented in Figure 7 are based on trading behaviour of single market participant. The phenomenon that causes such behaviour applies to great many market participants, which eventually affects the whole market depicting the behaviour in form of market price.

Let us consider market participant's allocated volume, just like in figure 7. Now there will be price component added to the figure, on a second y-axis. For simplification reasons, let this be a market where price and allocated volume are always the same. Figure 16 illustrates such situation:

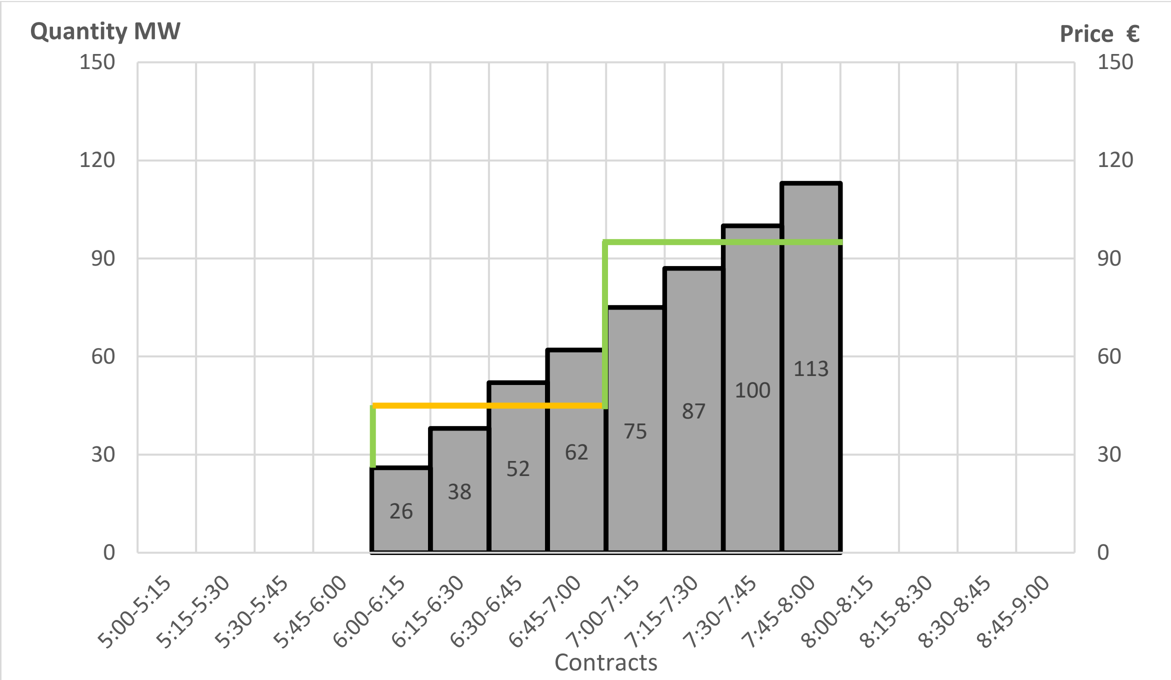

Figure 16: Illustration of intraday auction price formation and volume allocation based on day-ahead prices and allocated volumes. Green line represents volume allocated in day-ahead, but also price of the allocated volume.

In Figure 16 there is green line and grey columns. The green line represents hourly day-ahead price but also hourly day-ahead allocated volume. The volume is on left Y axis and the price is on right Y axis. Let us suppose that figure 16 represents increasing demand and thus the allocated volume is purchase from the market. The grey columns represent how the allocated volume looks like after intraday auction, in order to satisfy the 15-minute ISP condition. The allocated volume over green line means market participant had to buy extra electricity in the auction whereas empty areas under the green line means that market participant had to sell electricity in the auction. Let us consider the situation. During the first hour the allocated volume on day ahead market is 45 MW at price 45 €. The day-ahead price the increases during second hour to 95 € and allocated volume follows to 95MW. The price increase is linear with volume increase, and in order for market participant to be in balance one should allocate the volumes in ascending manner, just like depicted. Let us consider third quarter of first hour. In order to respect the day-ahead electricity pricing the third quarter should cost 52€, the value of third column, but also market participant should have 52 MW allocated on that quarter. The market participant is therefore short of 7 MW and needs to buy it in intraday auction.

Let us imagine situation where market participant buys 7 MW in intraday auction on third quarter at the quarter's real market price. The real market price is in this case 52€, as can be seen from figure 16. The allocated volume would look in this case 45 MW per quarter from day-ahead auction at price 45 € and 7 MW from intraday auction at price 52 €. The average price of the allocated electricity would be:

$$45\,MW \ast 45\,€\,/\,MW + 7\,MW \ast 52€\,/MW = 2389€ \qquad (7)$$
$$2389\,€\,/\,52\,MW = 46\,€\,/\,MW$$

The final price ended up being 46€ / MW, which is not the market price, the 52 € / MW. In order for market price to realize, the intraday auction price on the specific quarter should be:

$$\frac{X\,€}{52\,MW} = 52\,€\,/\,MW \leftrightarrow X = 2704\,€ \quad (8)$$
$$Y = \frac{2704\,€ - 45\,MW * 45\,€/MW}{7\,MW} = 97\,€/MW$$

The intraday auction price which should be given for 3rd quarter is 97 € / MW, which is higher than day-ahead price of the second hour. This is exact phenomenon we see in actual intraday auction prices from figure 15.

This can be interpreted that realized quarter hourly intraday auction price actually does not price the energy, but prices the error of day-ahead price on quarters. More specifically, it is not the energy traded on the quarters like in day-ahead, more like, the error between day-ahead hourly price and day-ahead quarter hourly price is traded on intraday auction. The day-ahead auction is the most liquid one, and market participants fix most of their positions already in day-ahead market. The intraday auction volumes are much smaller than day-ahead auction volumes. Therefore, higher volatility of quarter hourly prices occurs to fix the DA pricing error for the whole portfolio already allocated in day-ahead market. This finding completely denies the claim that intraday auction is separate market, which values energy prices in quarters. The purpose of intraday call auction is to fix day-ahead quarter hourly pricing, by measuring the error by setting a price for it.

The exceptionally high quarter hourly price spreads seen in Figure 15, show that there is steep day-ahead quarter hourly price increase between hours 6.00 and 8.00. The day-ahead price increases from 31€/MWh to 45 €/MWh in just two hours. Situation is reminiscent to illustration of figure 16. The intraday auction price indicates, that the prices need to be extra high on last quarters of the hour and extra low on first quarters of the hours to fix the pricing error that day-ahead auction has left on quarters. The intraday auction price thus does not reflect the price of energy, but the error of day-ahead auction.

Hence, intraday auction does not show the real market price for the quarter, rather the weighted average of intraday and day-ahead market is the real market price.

5.4 Forecasting error for the liquidity in intraday

The intraday call auction is not necessarily only about fixing the day-ahead positions. In addition to systematic need for market participants to balance their quarter hourly positions after day-ahead, there is also random component of forecasting errors bringing liquidity to intraday. Study by (Hagemann and Weber, 2013) finds that intraday liquidity stems mainly from the wind forecast errors, the solar forecast errors and the load forecast errors. Essentially the article says, that forecast errors of above-mentioned factors are traded in intraday in order not to suffer imbalance settlement fees. The forecast errors can thus be expected to influence the intraday prices as well. It is important to note, that the article analyses data from 2010-2011, when there has not yet been 15-minute intraday call auction in Germany. Thus, the findings in article are found to be valid for hourly, continuous intraday market. The big difference between continuous intraday market and auction market, is that continuous intraday market extends up to one hour before the delivery. There is thus plenty of time for updated wind forecasts to arrive which enables market participants to utilize the latest and continuously updating forecast in their trading behaviour. The intraday auction however, EPEX call auction in particular, occurs only three hours after day-ahead gate closure. During those three hours the forecasts might not change significantly, thus there might not be much liquidity originating from forecast errors, and therefore that might not be seen in prices. Another reason why forecast errors are not so visibly seen from the data analysis, is because the data used in analysis was average data from the whole month. The forecast errors are most likely affecting daily prices and seen as more or less random deviation from day-ahead price during a certain hour or hours. As the hours during which the deviations change from day-to-day the information might not reach the monthly averages. The fundamental findings of the article are considered to be valid for purposes of this thesis as neither the type of market nor the resolution is considered to dispute origin of liquidity in intraday – the forecast errors. The findings have been cited in other researches on the topic such as (Gürtler and Paulsen, 2018), therefore are used in this thesis.

The underlying assumption is that forecast errors bring liquidity to intraday market. However, it is difficult to state to which market the liquidity eventually goes to. Intraday auction is discrete auction, with no interconnectors, and thus the price of forecast error could be effectively priced in the auction. However, as the German intraday call auction occurs only 3 hours after the day-ahead auction, the forecast for the next day might yet be as accurate as needed to effectively trade the difference. There has been research conducted on this topic. Article by (Kath and Ziel, 2018) analyses the effect of forecasting on intraday call auction prices in German market. The article refers to publicly available forecasts, based on which the price forecasting models are created. The article cited three publicly available forecasts, TSOs load forecast provided at 10:00 d-1, the solar and wind power forecasts at 8:00 d-1 also provided by TSOs. The publicly available forecasts are often on hourly resolution and released only once per day. The article nevertheless concedes, that market participants use commercial forecasts on 15-minute resolution, which presumably are more accurate than TSO forecasts. The article assumes (Kath and Ziel, 2018, fig. 1), that updated renewables forecasts are used for intraday-call auction, from 30-minutes before the auction occurs. There thus might be discrepancy between the forecasts for day-ahead and for intraday call auction. The latter forecast is presumed to be more accurate than forecast for day-ahead auction, as it has smaller granularity and is closer to the time of delivery. The difference between these two forecasts can be considered a forecast error of day-ahead forecast. The forecast error is then traded in intraday-call auction on 15-minute resolution. If this holds true, there is also another component affecting intraday call auction prices besides the systematic need to balance. The forecast errors, at least to some extent, might be also traded in the same place; thus, this brings some variation to findings about intraday call auction prices. What is remarkable to note, that not all intraday auctions especially in future will be held three hours after day-ahead auction. If pan-European intraday auctions were to become true the auction timings would be 15.00 d-1, 22.00 d-1 and 12.00 D. For the gate closure of latest two auctions there is plenty of time for forecasts to update with more specific information and thus affect the trading behaviour of market participants. There have been studies done on the topic how does wind forecasting accuracy increase over time up to delivery hour. A study by (Holttinen, 2005) measured absolute errors of wind power predictions over the one year period. The study was based on realized wind production data from Denmark in 2001. The study found out, that according forecasting model WPPT version 2, 90% of energy will be known 1 h before the delivery, 70 % of the energy will be known 9 h before, 60 % of energy will be known 24h before and only 50 % of the energy will be known 36 h before. Although the data is very old, and the wind farms have developed to probably more predictable way of operation as well as forecasting models and techniques have evolved over the time, it can be said that forecasts become more precise over the time closer to delivery. There is also other literature ending up with the same conclusion (Weber, 2010), (Zhang

Jie et al., 2015). It can thus be presumed that updated forecasts do affect the trading behaviour of market participants, which will become particularly evident when chronologically later auction will be introduced. More importantly the forecasting errors of renewable energy affect the system stability and need for balancing. As there is however no intraday auction held closer than 9 h for the first delivery hour at best and 33 h before the last delivery hour at worst, without any cross-border capacities, it is most probable that with such market design forecasting error liquidity is traded over continuous intraday market for most part. The article by (Kiesel and Paraschiv, 2017) has studied econometrics of continuous intraday 15-minute prices. It was clearly identified in the article that forecasts bring liquidity to 15-minute continuous trading. The factors affecting intraday liquidity will be investigated closer.

5.5 Impact of continuous intraday market on system stability

It is important to bear in mind that basis for power system balance is aggregate balance of each BRP. The electricity market at the moment is built around day-ahead, as there is most liquidity in day-ahead market. The day-ahead market is held at time when knowing exact amount of power production during delivery hour is non-predictable. Thus, it can be thought that the higher the amount of renewables in power system, the more imbalances for BRPs managing VRES portfolios during delivery hour thus the more balancing has to be done. According to this conventional wisdom, as renewables enter the power system in increasing amounts the more balancing volume is required and thus higher the balancing costs (Batalla-Bejerano and Trujillo-Baute, 2016). Also, this is part of the cause of declining frequency quality in Nordic countries as mentioned earlier(Nordic TSOs, 2016). As research article (Batalla-Bejerano and Trujillo-Baute, 2016) has found such impacts of renewable generation on Spanish electricity market, the German electricity market has been and exception (Hirth and Ziegenhagen, 2015). Empirical work by Hirth and Ziegenhagen has challenged such conventional wisdom, introducing descriptive statistic about German balancing market volumes decrease simultaneously with increase of share of VRES in power system. The phenomenon is commonly referred in literature as German Balancing Paradox. The article (Koch and Hirth, 2018) further investigates the phenomenon and comes to a conclusion that ultimately the German balancing paradox is caused by efficient electricity markets that enable market participants to trade themselves to balance.

It was identified by the article that combined installed generation capacity of wind and solar power had grown from 54 GW to 99 GW during years 2011-2017. As the new installed capacity tends to have higher capacity factor, the increase in annual energy production is even higher ranging from 69 TWh to 145 TWh for the respective time period. At the same time average FRR Capacity procured, both upward and downward reserve combined during years 2011-2014 has been 8.8 GW, which has dropped by 20% by the end of 2017 to average of 7.2 GW. The amount of activated reserves had declined even more, it dropped from well above 7 TWh in 2011 to 4 TWh in 2017, a 45 % of decline in balancing energy.

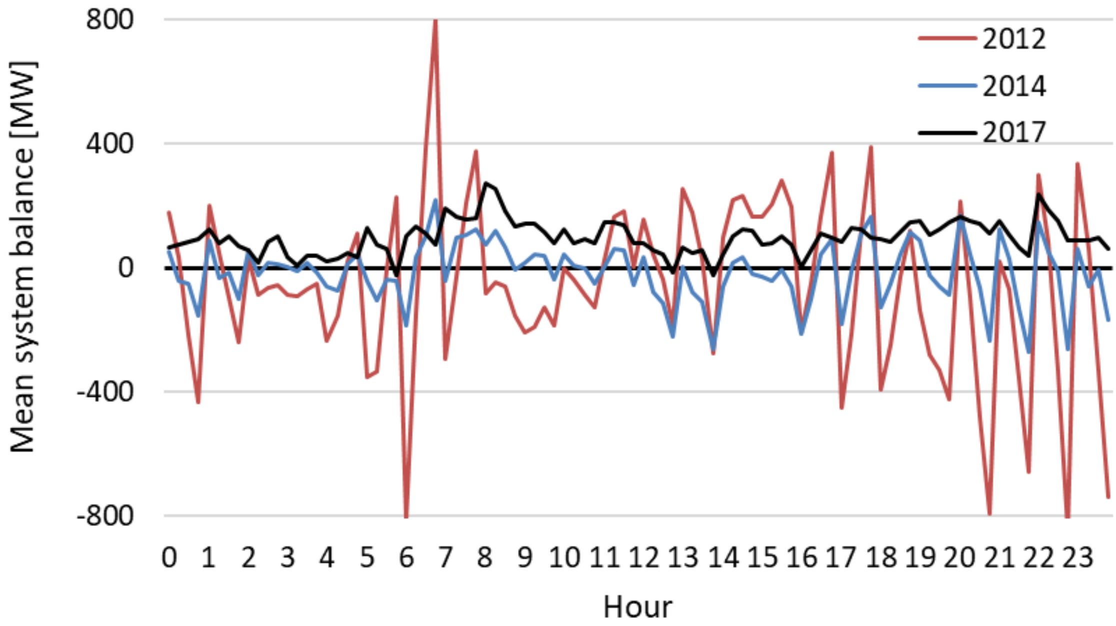

Figure 17: Average German system balance per quarter hour for 2012, 2014 and 2017 (Koch and Hirth, 2018)

Figure 17 above shows the average system balance per hour for 2012, 2014 and 2017. The red line, which depicts average system balance per hour in 2012, has significant variation especially in the morning. The system has been on average short of power by -800 MW and long on power 800 MW during the same hour. An average 1600 MW swing during the same hour is terrific and requires a lot of attention from system balancing perspective. The blue and black line which represent system balance per hour in 2014 and 2017 respectively have evened out the curves, and although there are systematic imbalances, the swings are much lower. It can be found from the figure that need for balancing has clearly decreased over the years, as the curves have flattened over time. It can be expressed in other words, the burden of system balancing has shifted from balancing markets run by TSOs, to other instances.

The other instances argued by the article are intraday markets provided by EPEX SPOT. EPEX SPOT launched quarter-hourly trading products on German intraday market in December 2011 and the quarter hourly intraday auctions in December 2014. After the launch, the liquidity on these markets has skyrocketed. Between years 2012 and 2017 the liquidity of quarter hourly contracts has increased from 1 TWh in 2012 to 10 TWh in 2017. The article finds that grid imbalances have declined hand in hand with increase of trading on quarter hourly contracts. (Koch and Hirth, 2018)

Let us further analyse the German market design. The day-ahead trading volume was 233 TWh in Germany on EPEX SPOT market. The overwhelming amount of liquidity is on hourly resolution. The intraday liquidity in Germany was 47 TWh in 2017 of which around 10 TWh has been on 15-minute contracts. Therefore, the liquidity on continuous intraday hourly market in Germany is around 37 TWh. From these numbers there can be drawn a conclusion that both day-ahead and intraday markets, also on 15-minute resolution, have been very liquid. Let us consider closer the 15-minute liquidity. Out of 10 TWh of total quarter hourly intraday liquidity, around 50 % has been traded on intraday auction and around other 50 % has been traded in continuous market. (Epex Spot, 2018)

Now let us consider what is traded where. According to the article (Neuhoff et al., 2016) continuous intraday 15-minute market and 15-minute intraday call auction are not of substitutional nature to each other. In other words, one market doesn't compete for liquidity with another market. The article believes that this is due to timings where liquidity distributes. Whereas continuous intraday auction is used to correct the unexpected events closer to the delivery hour the intraday auction is used to correct the known factors based on day-ahead auction information. In other words, intraday auction at 3 pm D-1 is used to smoothen day-ahead positions to match the 15-minute ISP requirement, using so called 'old information'. (Neuhoff et al., 2016) This supports findings of this thesis in price analysis of intraday auction prices. When some new information enters the market, continuous intraday market is used to utilize this information. According to common sense, higher fluctuations such as large-scale forecast errors can be adjusted in hourly continuous market whereas finer adjustments on quarterly basis can be done on 15-minute continuous market.

It was found in the article (Koch and Hirth, 2018) that intraday auction helps balancing the power system. The article has identified the same variables as this research, namely wind production solar production and load fluctuations. The finding relates to the forecast errors addressed earlier in this thesis. Ultimately there are two kinds of errors, as mentioned previously, level error and phase error. It could be said that phase error is uncertainty in timing and level error is uncertainty in gradient. Because, solar generation and load profile are systematic errors, frequently following diurnal pattern, i.e. solar generation increases in the morning and decreases in the evening – same goes for load. As one day ahead before the occurrence of such variables as solar and load is relatively accurately known, this eliminates the phase error. Therefore, as electricity is allocated in day-ahead, the systematic error is fixed in the auction on variables which are predictable. These systematic errors according to the article have declined by 80% after introduction of intraday auction (Koch and Hirth, 2018). There is still some uncertainty in level error, i.e. in the gradients of solar and especially load gradients, but those can later be addressed in continuous hourly intraday market. The article finds that it is difficult to predict wind power production at time of intraday auction, because the phase error still applies for win power, and makes prediction difficult at 3 pm D-1. As the wind power production is not so easy to predict in intraday auction, therefore the continuous intraday would be better place to manage the balancing for wind power producers. EPEX intraday market holds substantial amount of liquidity, both on hourly and 15-mintue contracts.

The research by (Neuhoff et al., 2016) analyses the trading volumes in the last 3 hours before the delivery of continuous quarter hourly intraday market. The research finds that most traded volume is on the last hour before the delivery start. EPEX intraday continuous extends up to 5 minutes to the delivery hour, which gives wind power producers a substantial amount of time to fix the production plans in line with latest forecasts and trade themselves to balance. This is a very important finding, as it signifies that most trading is done on 15-minute products right before delivery on the delivery hour, thus directly competing with balancing market.

Considering these findings, there could be drawn a conclusion, that intraday volumes compete for balancing market volumes. That is the conclusion of research by Koch and Hirth as well. In other words, intraday auction is used to trade day-ahead positions on quarter hours, whereas continuous intraday both hourly and quarter hourly market fixes the forecasting errors which are not considered in intraday auction. Intraday auction and continuous intraday market do not compete for liquidity amongst each other, but together compete for balancing and reserve market liquidity. Due to liquid intraday markets, liquidity has shifted from balancing markets to intraday markets and need for balancing has decreased.

Considering the system imbalance curves from figure 16, it could be signified that liquidity on 15-minute resolution contracts is quite purely dedicated for system balancing. This conclusion stems from vision that sum of individual BRP imbalances equal to system imbalance. The vision holds even more so true for German market, where passive balancing is forbidden by legislation. The German legislation forces BRPs to actively trade themselves to balance. The 15-minute trading thus addresses directly BRP imbalances, as most of the liquidity is on hourly contracts, and clearly seems to have impact on system imbalance as can be seen from figure 16. The significance of the findings is, that according to article (Pape et al., 2016) balancing done by market participants is always cheaper than balancing done by the TSO. Therefore, every MWh traded in 15-minte resolution intraday market potentially brings savings to the system.

6 Quarter hourly resolution for Nordic power system

6.1 Impacts on market

There has been identified two impactful factors in German market design that are beneficial for the power system. Those are intraday auctions that help power system get rid of systematic imbalances and other is sufficient liquidity on quarters close to delivery hour that help BRPs to reach final balance. Will purely implementing this market design bring the same benefit to Nordics?

Presumably 15-minute ISP in the Nordics is expected to bring the same benefits as it has brought to the German market and power system. System will have less structural hourly imbalances, less imbalance jumps, system will be balanced by market not by TSOs. Given that consumption will be metered in the Nordics on 15-minute resolution, implies ever more reasons for demand to shift to quarter hourly resolution, thus to intraday. However, it is not so simple. There is one major difference between German market and Nordic market, the interconnectors. The interconnectors play pivotal role in Nordic electricity market. The Nordic synchronous area is divided into 11 delivery areas, all connected with interconnectors. This is not the case for Germany, where everything happens within one market area. In addition, there are various HVDC interconnectors which connect Nordic synchronous area to other synchronous areas such as Baltic, Central European and soon to Great Britain as well. There is already up to 8 000 MW interconnector capacity stemming from Nordic synchronous area, to somewhere else. This adds a great amount of complexity to the 15-minute ISP implementation in the Nordics, first and foremost, by restricting cross zonal gate closure time for one hour before the delivery. This already is a major setback, as most of 15-minute product liquidity is traded during the last hour before delivery, as previously discussed. Thus, the most pivotal trading for system balancing, from chronological point of view, the 15-minute products before delivery, is crossed out form Nordic power system.

This thus implies, that the ACER methodology on cross zonal gate closure in intraday, which forces rolling cross zonal gate closure with respect to ISP will not give full benefit in Nordics. The issue in German continuous intraday market with gate closure is, that even though there are four 15-minute products during an hour, they all close at the same time. This creates an inefficiency, of uneven latency of available information for trading purposes. The information used for trading on 1st quarter of an hour is potentially one second old before delivery at the time of gate closure. The information used for trading on last quarter of an hour, is at minimum 45 minutes old or late. Thus, there is systematically more uncertainty when trading on last quarter compared to first quarter of an hour. Given that gate closure time will be rolling, the information available of each quarter is standardized, always potentially 1 second old. Even if there will not be cross border 15-minute gate closure up to delivery in Germany, the inter zonal rolling gate closure will be of great benefit as well. In the Nordics however, rolling gate closure will standardize the information used as one-hour old information, as cross zonal gate closure must be at least one hour before delivery.

There arises a concern, why should there be cross zonal gate closure one hour before the delivery in Nordics. The ACER decision on intraday cross-zonal gate opening and intraday cross-zonal gate closure times the intraday gate closure is to be set at most one hour before the start of the relevant market time unit. Thus, it can be closer to delivery, but at most one hour. In the explanatory document for the intraday cross-zonal gate opening and gate closure times the decision to keep 60 minutes is further explained (ENTSO-E, 2016).

It is said in the document that all TSOs have explored the time span needed for scheduling and balancing purposes and come up with 60 minutes of time needed. The reason thus lies, at least according to this input, that the 60 minutes is needed to have for balancing and scheduling purposes. It is argued in the document, that in the future the time can be shortened after harmonization of balancing mechanisms is implemented as foreseen in the EB GL. (ENTSO-E, 2016, chap. 4) Thus it can be deduced, that as cross-zonal gate closure in the Nordics is one hour prior to delivery, the Nordic TSOs truly need the hour of time for balancing and scheduling purposes. This could be related to estimating effects of interconnector flow to the power system, thus scheduling the balancing to counter imbalance jumps for example. It is thus assumed in the thesis, that as long as interconnectors are on hourly resolution, no change to cross-zonal gate closure will occur.

As the interconnectors close 60 minutes before delivery, there arises a question, does there have to be cross zonal market up delivery. Would it be possible to balance the system with intraday market and still gain benefits from 15-minute trading without cross border trade even in the Nordics? In theory, there could be 11 local markets one per each delivery area in the Nordics with local gate closure up to delivery hour. In this manner market participants could trade within each delivery area and establish quarter hourly balance within the delivery area. Given that each delivery area would balance itself, the whole system would reach balance. This is not so straight forward, however. The problem lies in market structure of Nordic countries. There are statistics provided on intraday volumes in Nordics per nature of trade by ACER in their market monitoring report from 2017 (C. ACER, 2018, fig. 26). According to the statistics, Finland has the highest intrazonal intraday liquidity of all Nordic countries, which is only 40%. For market areas in Sweden and Norway the intra zonal liquidity is below 10 %. This means, that most of all intraday trading in the Nordics is cross-zonal. Of all areas, in Nordics only Finland could effectively self-balance the market area without cross-zonal intraday market, and even so the market efficiency would be reduced greatly. In other words, in the Nordics market participants nearly always tend to trade between different price zones, not within one like in Germany for example. Therefore, even if continuous intraday gate closure would extend up to delivery within price zone, it would have little effect on efficient system balancing, as there would not be counterparty with whom efficient trading would occur. Thus, in order to gain same benefits from 15-minute ISP as in Germany, the cross-zonal gate closure should be introduced up to delivery, on the side to 15-minute contracts.

6.2 Impacts on transmission system

At the same time, the declining frequency quality in the Nordic synchronous area has been identified as a great concern amongst TSOs. The frequency quality in Nordic countries has been declining over the decade already as mentioned earlier, but TSOs predict that the trend will remain the same due to ongoing changes in the power system (Nordic TSOs, 2016). The large trends decreasing the frequency quality are ever increasing amount of intermittent generation, mainly wind power, Swedish nuclear phase-out and new interconnectors to Continental Europe up to year 2025 (Nordic TSOs, 2016).

The article has identified challenges that make maintaining an adequate frequency difficult with regard to these high-level trends. These challenges include larger structural intra-hour imbalances, changes around hourly shift and reduced access to reserves. The article acknowledges that trend towards increasing intra-hourly imbalances will grow in future, especially during morning and evening peaks when there are large shifts in consumption, production and the HVDC links. The report has modelled imports and exports of Nordics during average winter week of 2025. The model predicted that imports and exports of Nordics during average winter week in 2025 and there was found gross daily swings from exports to imports. It has been specifically identified in the report that large flow changes in HVDC links will cause significant balancing difficulties. Important fact to bear in mind is that Nordic synchronous area is relatively small compared to amount of interconnectors stemming from it. Therefore, collective cross-zonal interconnector ramping affects frequency of Nordic power system more than the one larger power system. It can be thus said, that interconnectors pose a heavy challenge to maintain system balance, due to capability of faster ramping than rest of power system. However, it has also been acknowledged that efficient use of the HVDC interconnectors in the day-ahead and intra-day market requires faster changes in flow direction than are currently accepted, which will further increase intra-hour imbalances if mitigation measures are not introduced. According to the article one of these mitigation measures could be further restriction of ramping limit on each HVDC interconnector.

There are thus clearly two approaches to treat interconnectors in the Nordic electricity market. On one hand allowing fully market-based flow over interconnectors is the basis for electricity markets in Nordics, because there are eleven delivery areas within the Nordics. On the other hand interconnectors play important role in system adequacy, such as frequency quality, which needs to be maintained on stable level. These two approaches somewhat contradict with each other. It could be argued, that if interconnectors would be on 15-minute resolution the difference between market-based flow and system balancing would be narrow, potentially one contribution for another. As Nordics are fragmented into eleven delivery areas, it could be said, that for Nordics to gain significant benefit from 15-minute ISP the interconnectors need to be addressed in quarter hourly resolution. Otherwise, most of the trading important for system balancing would occur within delivery area, which does not bring social welfare, which wholesale electricity markets are expected to bring.

6.2.1 Ramping restriction

The ramping limit currently in the Nordic region toward the continental Europe is 600 MW/h. This limit stems from ramping speed, which is 30 MW/minute, where interconnectors are ramped over 20 minutes, 10 minutes before the change of the hour and 10 minutes after. Thus the 600 MW/h. (Nordic TSOs, 2018a) There is not any evidence that Nordic TSOs would tighten or loosen the ramping restriction. However, the future is challenging. Three new HVDC interconnectors are under construction and deployed in near future from Nordic synchronous area accounting for total of 3200 MW additional capacity by 2021. Coupled with increasing wind power production this will increase the balancing challenge to Nordic power system. Already today ramping limit restricts the market from perfect operation and thus costs in terms of social welfare. According to statistics from 2016, on about 7 % of the hours in 2016 trading was restricted due to ramping restriction (Copenhagen Economics, 2017). In other words, trades that would have happened in perfect market could not happen due to ramping restriction, implying a cost in form of decreased social welfare. If ramping restriction would be tightened say to 400 MW/h, the market would be restricted even more.

In the explanatory document to Nordic synchronous area proposal for ramping restrictions for active power output (Nordic TSOs, 2018b, chap. 5) is stated that with increased amount of HVDC interconnectors, changed flow pattern and the introduction of

15-minute ISP requires that ramping limits, ramping periods and methodology for determining these limits need to be re-evaluated. It is also proposed in the proposal itself (Nordic TSOs, 2018a, Article 4), that there will be a ramping restrictions on BRPs representing power generating modules in Finland, Norway and Sweden when their hourly production plans change more than 200 MW at hour shift. In that case BRPs would need to reschedule their production plan with quarterly steps 15 minutes before and after hourly shift to better match the consumption pattern. The detailed terms and conditions would be specified on national level. This however still needs to be assessed, as mentioned in explanatory document. Thus, it could be said, that one approach to solve the declining frequency problem is to limit market from free functioning and try to control the assets to some extent to match system needs better.

On the contrary, it is envisioned that after implementation of 15-minute resolution, the ramping limit could be relaxed. This would be remarkable change for Nordic power system. If cross-border flows would be allocated on quarter hourly resolution, then the interconnectors could be ramped 7.5 minutes before and after each quarter shift, effectively aggregating to continuous ramping over the whole hour. If the ramping speed would be considered the same, 30 MW/h, the continuous ramping approach would result in 1800 MW/h ramping limit (Copenhagen Economics, 2017).

Let us assume, that ramping speed in case of continuous ramping would decrease to 20 MW/h to cause less stress on power system, thus resulting in 1200 MW/h hourly ramping limit. There are two separate effects of such change, first the quarter hourly imbalance jumps would be supposedly smaller than hourly imbalance jumps as former ones would correspond to grid changes real time. Therefore, less tuning of interconnectors would be needed by default. Second, the immediate ramping limit would be reduced to 300 MW/quarter, whilst the hourly ramping limit would be increased to 1200 MW/h, given that ramping speed is 20 MW/h. The impact of such arrangement would mean less ramping speed, thus smaller stress on power system in form of immediate ramping limit (300 MW vs. 600 MW) and longer ramp times while simultaneously increasing hourly ramping limit. Inevitably continuous ramping would relieve stress from power system balancing, in particular of imbalance jumps resulting by HVDC, thus increasing frequency quality. In order for continuous ramping to become reality the flow on interconnectors, especially HVDC interconnectors, should be allocated on 15-minute resolution. However, as flow for the first time on interconnector is determined in day-ahead market, which operates on hourly resolution, a contradiction arises. There is no way to make electricity flow on quarter hourly resolution over the interconnectors, unless day-ahead market switches to quarter hourly resolution. The report by (Copenhagen Economics, 2017) argues that if day-ahead flow would simply be divided by four on each quarter, intraday market could fix the flow on 15-minute resolution. For instance, day-ahead market has determined flow on two consequent hours in some direction. The flow is restricted to chosen direction by ramping limit. In the intraday market, the flow would be split on each quarter. Quarter hourly intraday market would give opportunity for market participants to start the ramp up earlier. Consequently, the relieved ramping limit would free capacity for intraday market, which could potentially be used for trading.

The report does not reveal which intraday market (auction vs. continuous) is thought of in their illustration, thus both options will be considered separately. In any case such arrangement would lead to some form of inefficiency due to following reasons. First, the reference prices and clearing would have already been established with respect to ramping restriction, thus impacting social welfare. Second, and most importantly, the capacity available for intraday market on the quarters is already restrained by the ramping limit after day-ahead auction. This already sets a pre-condition that no trading can be done during the hour, which is restricted by ramping limit in intraday, in example above the second hour in intraday market. In case of continuous intraday market, the quarter hourly trading could start the ramping on earlier quarters of the first hour. The ramping restriction could thus be relaxed at the hour shift. However, the flow still needs to respect the quarter hourly ramping limit which is 450 MW/quarter or 300 MW/quarter, depending by ramping speed, which is not considered in the report. Say continuous intraday would relax ramping limit so that theoretically the flows between two hours are no longer restricted by ramping limit. In order to benefit from ramping limit relaxation, trading should occur on second hour thus utilizing the freed capacity. This could be done in continuous intraday, on first come first serve principle, that capacity would free from 1st quarter of second hour as flow is increasing on 4th quarter of first hour. If so, the freed capacity would not be used optimally in auction clearing, thus not resulting in capacity pricing nor in social welfare optimized matching. Therefore, cross-zonal intraday auctions need to come to play. At the time of the auction, the capacities are halted, and flows are aggregated between day-ahead and continuous intraday. At this time, the day-ahead flows have been affected by continuous intraday trades, thus re-calculation of ramping limits is possible, thus freeing capacity from second hour and clearing market systematically with respect to freed capacity. The ramping limits could be re-calculated in first intraday auction right after day-ahead, however, little changes are anticipated as little new information has entered the market. The possibility to change the ramping in first auction largely depends on allocation constraints of all hours combined, such as quarter hourly ramping limits, hourly ramping limits, capacities available, etc. Therefore, continuous intraday would be important market to relax the ramping limit.

Based on discussion above it could be said, that quarter hourly intraday auction and quarter hourly continuous intraday would bring benefit to power system in terms of ramping limit relaxation and system control, even though not as much as day-ahead market on 15-minute resolution. It can be thus said, that 15-minute ISP itself is not enough to bring benefits to full extent. It is necessary to have 15-minute resolution markets to enable market participants, the BRPs, to change their trading behaviour in correct direction from system perspective.

6.3 Market coupling benefits

Market coupling for the most part is based on price differential between areas, equating to optimized producer and consumer surplus thus resulting optimized interconnector flow. In order for interconnector flow to occur two things are needed, harmonized contracts and interconnector capacity. Currently, contracts between Nordics and Central Europe are not harmonized. There are many interconnectors connecting two respective synchronous areas, such as NorNed, Kontek and Baltic cable and more to come in near future. On one side of the cable, such as in Germany and Netherlands, settlement occurs on 15-minute resolution, thus creating liquidity pool on quarter hourly resolution. On the other side of the cable, in the Nordics, all liquidity is on hourly contracts as there are no products on finer time resolutions. This leads to situation where products are not harmonized between different markets, leaving central European quarter hourly pool of liquidity completely inaccessible for any Nordic market participants. Merely a legislative change of ISP from one hour to 15-minutes will not change the status quo of separate orderbooks. It is however possible to trade on 15-minute contracts cross-border on panEuropean intraday platform XBID already today, for example between Germany and Austria. It is thus presumable, that there indeed will be shared orderbook between Central Europe and Nordics after implementation of 15-minute ISP. The article (Copenhagen Economics, 2017) had also found that harmonization of products would be one of potential benefits from 15-minute ISP.

There is alternative approach to consider the market coupling benefits. The markets are already coupled between Nordics and Central Europe on hourly resolution. First, in day-ahead, second in continuous intraday on hourly resolution. The day-ahead market and continuous hourly intraday market hold the most liquidity already, so it could be said that most of market coupling benefits are already achieved. As most of the continuous trading occurs close to delivery hour, in order to get any benefit from harmonized products, there should be capacity between Nordics and Central Europe up to delivery hour. However, this is already an issue for hourly continuous intraday, as there might not be capacity left after day-ahead for those interconnectors. Thus, the bottleneck for liquidity sharing is not the unharmonized contracts rather it is the interconnector capacity. If there is not capacity after day-ahead, the intraday coupling will bring no benefit.

This is not so straight forward, however. It has become evident from articles referred in this thesis, that the more renewables there are in the power system, the more valuable the latest information to the market is. There is a reason for most of 15-minute trading occurring within an hour to delivery, as the latest information can be utilized most efficiently. It is not for granted, that the flow which has been established in day-ahead, would remain the same in intraday, on quarter hourly resolution up to delivery. If there is a change in wind power forecasts for example, which occurs relatively close to delivery, it might affect short term trading behaviour of market participant and create a financial incentive which would turn the flow around on interconnector. If there is large changes in wind power forecasts, the situation described could happen already in continuous hourly intraday market, thus quarter hourly resolution would not bringing much added value in terms of liquidity. However, as there is 15-minute ISP in Germany and Netherlands already, the forecast changes affect the quarter hourly position in the first place. It could be thought, that if forecast error occurs, which leads to reverse flow on interconnector due to trading on hourly resolution, the trading for balancing will inevitably occur on 15-minute resolution as well. Therefore, harmonizing contracts will provide an opportunity for market participants from both synchronous areas for optimal balancing, at least in one direction of interconnector, maybe in both. Trading for balancing however, just like research has shown, will occur as close to delivery hour as possible where latest information is in use to fix the final position. We can thus come back to conclusion where most of 15-minute continuous intraday benefits occur close to delivery hour. At this point the benefits of short-term 15-minute trading face the same problem as rolling gate closure, the closure of interconnectors one hour before delivery. In other words it is impossible to trade on 15-minute resolution close to delivery over interconnectors, because cross-border gate has closed. This is not necessarily the case for balancing market.

6.3.1 Balancing market integration

At the time thesis was written, the balancing market gate-closure is 45 minutes before the delivery, on hourly resolution. The same time when production plans need to be submitted to TSOs. It is discussed in the chapter 3, that the time of gate closure of balancing market will supposedly shorten to 25 minutes before delivery hour. It envisioned that at the time of 15-minute ISP, the balancing market will also move to 15-minute resolution. Even with these changes, the uncertainty of balancing providers is higher than in intraday given the rolling gate closure. Even at the time the thesis was written, in German intraday market it is possible to trade on 15-minute resolution up to delivery hour, on all four quarters. The issue is that it is not possible to trade with latest information on every quarter just like discussed in chapter 7.2. However, if there will be rolling gate closure implemented up to delivery in German intraday market for example, 15-minute products would close right at the start of delivery of the product, making latest information possible to utilize. This sort of arrangement is very competitive against balancing market, even with gate closure up to 25 minutes before the hour. Even if balancing market would have 25-minute rolling gate closure with respect to every quarter, continuous intraday would still be more accurate. Why is balancing market of such importance then?

The two biggest differences between balancing and intraday market is that balancing products have obligation to delivery and the products are standardized. Depending on reserve type aFRR or mFRR there are standardized full activation times and balancing products are often bound to a location. The biggest difference between aFRR and mFRR, is that aFRR reserve is activated automatically without any human intervention (Fingrid Oyj, 2019b). On the contrary the mFRR order needs to physically be accepted by the TSO. As the aFRR reserve reacts to frequency deviations, it cannot be substituted by orders from intraday market, because the products differ fundamentally by the nature of execution. The mFRR nevertheless is subjected to substitution by intraday trading, just like the research by (Koch and Hirth, 2018) suggests. It is not so straight forward, however. The obligation of delivery largely separates these two markets. When a trade in intraday occurs, the trade affects portfolios of both market participants. Both market participants are responsible for conducted trade, one’s portfolio has gained energy, the other one’s has lost it. But there is no legal responsibility for market participant to affect the physical production/consumption as a result of the trade. This could be named as portfolio trading, whereas mFRR market is asset trading. When TSO accepts order from balancing market, the market participant which’ order is accepted, is obliged to deliver the electricity, and the delivered amount is physically measured by TSO. In balancing market, there is no counterparty, when TSO accepts an upregulation order, the market participant needs to produce the amount, but no-one is obliged to consume it. Therefore, it could be said, that mFRR is used to control or at least affect the frequency in the grid. Moreover, the mFRR asset’s location is known, which is important information when balancing the whole synchronous area.

This leads the discussion back to interconnectors. The market flow can be whichever direction on interconnector up to maximum capacity. The interconnectors close one hour before delivery, thus the full gain of 15-minute trading cannot be utilized. However, it is never known, whether there will be up-regulation or down-regulation need and on which side of the interconnector. It was earlier identified that ramping constraint and fully utilized capacity in day-ahead restrain intraday trading, especially close to delivery if the so-called left-over capacity is utilized. However, it does not necessarily restrain TSOs to balance the power system using the HVDC interconnector. The focal point is, that order book exists on other side of interconnector in intraday market therefore, why not to utilize them for balancing purposes. Given that the order book is with rolling gate closure with respect to 15-minute product, it gives a large potential for TSOs to balance the power system real time for cost of intraday electricity, which is a priori cheaper than balancing electricity.

For example, on 31st of January 2019 at 12.00-15.00 up regulation price in SE4 was 267€/MWh. The intraday market price during these four hours was somewhere between

40 and 70 €/MWh, both on hourly and quarter hourly resolution (Epex Spot, 2019b, sec. EPEXSPOTINTRADAY CONTINUOUS). The total scheduled flow on interconnector from SE4 to DE was 521 MW, 468 MW, 433 MW and 368 MW during respective hours. (Nord Pool Group, 2019, sec. Regulating prices, Total scheduled flow, Nord Pool Intraday) Given that capacity on the cable is 615 MW, there was capacity on every hour. Instead of using local resources for balancing for up-regulation price, it is possible for TSO to accept an intraday order from Germany for significantly cheaper price and subtract the amount from interconnector flow.

Now there arises a question, why wouldn't this be possible already today, in hourly resolution. The problem with such arrangement in hourly resolution is largely related to intra-hourly imbalances. If Nordic TSO activates hourly intraday order from Germany, there is no guarantee about precise timing when market participant will deliver electricity. At worst, the gain of balance SE4 area gains as result of the trade may be loss of balance in Germany. When trading will go to smaller granularity, coupled with German legislation that obliges market participants to trade themselves to balance, there is supposedly higher chance that the electricity will be physically delivered during the quarter. This could be expected more so, if German intraday market would have rolling gate closure. In such case, there could be raised concern, whether the actions of Nordic TSO would affect German power system balance. However, if Nordic TSO matches order from German intraday market, in theory the German power system balance would be in status quo, as some of German market participants is obliged to delivery energy that is subtracted from interconnector flow. In turn, if Swedish intraday market would have cheaper intraday electricity than German balancing market, German TSO could perform same set of balancing. What makes balancing over interconnectors particularly interesting case, is that it suffices the criterion of mFRR balancing. The activation time criterion is fulfilled, as the interconnector can be physically tuned, with ramping speed often exceeding the one of conventional generation. Also, the location of interconnector is known, thus the location criterion for analysing intra-zonal bottlenecks is also known.

In theory, TSOs could net imbalances via interconnectors already today. If delivery areas on different sides of interconnector need balancing in opposite direction, for instance up-regulation in Sweden and down regulation in Germany, it could already today be netted in interconnector flow. The difference is, that today it is not known what is going to happen during delivery hour, will the system be short or long on power, as that is largely determined by structural imbalances within an hour. Thus, if TSOs come to an agreement to imbalance net the flow over interconnector, for the beginning of the hour based on current information, the information might be old in the end of the hour, and the flow would not contribute as much to system balance. The fundamental change that 15-minute ISP coupled with rolling gate closure brings, is that there will not be any delivery hour after the change. To make possible avoiding balancing activation in balancing market by activating orders from intraday market both sides markets around interconnector need to standardized products. As there is no 15-minute ISP in Sweden, thus no 15-minute intraday market, this is not possible during the time the thesis was written. Therefore, implementing 15-minute products in intraday in Nordics, will potentially bring market coupling benefits not only in intraday, but in system balancing as well.

7 Conclusion

The thesis analysed impact of 15-minute imbalance settlement period to Nordic electricity market. It was identified in the thesis, that there are many inefficiencies hourly imbalance settlement period causes to the power system. The most influential inefficiencies were systematic imbalances due to imbalance jumps both within areas and over interconnectors as well as possibility of netting imbalances over an hour. All these combined have already caused a declining frequency quality in Nordic power system and is expected to do so in future as well.

It is identified in the thesis, that there are other regulatory changes that will enforce as 15-minute imbalance settlement period will be introduced. All these changes combined will greatly influence the Nordic market model. Generally, cost of imbalance will be higher with less opportunities to net the imbalances. This is expected to bring liquidity to intraday markets in purpose to find marketplace for balancing for BRPs. In order to assess the impact of 15-minute imbalance settlement period, the econometrics of German intraday call auction are analysed. The analysis was concluded to find impact of 15-minute imbalance settlement period on market participants' bidding behaviour. The hypothesis was, that intraday auction prices should have even some indication of structured prices, because market participants are forced to buy and sell electricity within the same hour. Three main findings were found out form the analysis:

1. Intraday auction's quarter hourly prices are very structured and systematic, revolving around day-ahead prices on hourly resolution. The auction price volatility is influenced by day-ahead price pattern revealing:
2. Intraday auction is complimentary to day-ahead auction, where little new information is traded, rather day-ahead positions are fixed to correspond 15-minute imbalance settlement period. This leads to situation that:
3. Ultimately intraday auction does not price energy, rather it prices the pricing error of day-ahead auction, resulting in a systematic price formation of intraday auction.

Findings supported the hypothesis. Based on other literature it was found, that quarter hourly intraday auction and continuous market combined, have helped German power system to reduce greatly structural system imbalances. The pre-condition for this is sufficient liquidity in intraday market both on hourly and quarter-hourly contracts. Also, important factor identified is gate closure extending up to delivery, which reduces latency of information available, thus the uncertainty of market participants. Based on these observations, a conclusion can be drawn, that wholesale electricity market design affects power system stability and need for balancing.

The answer to first research questions is that after introduction of 15-minute ISP, the market participants will actively seek themselves to balances on 15-minute contracts and closer to delivery to avoid imbalance fees. This is expected to bring liquidity to intraday markets, and greatly increase interest to quarter hourly contracts and auctions, which are yet inexistent in Nordic market model. With respect to principle of market model serving needs of market participant convenient wholesale electricity markets need to be established, with 15-minute products, preferably both intraday auctions and continuous intraday market.

It is identified in the thesis, that as whole German market is only one delivery area, the concept of system balancing by efficient functioning of intraday markets cannot be transferred to Nordics in full extent. This is because Nordic power system is divided into eleven delivery areas, where electricity is mostly traded cross-zonal between different delivery areas. Therefore, if interconnector gate closure remains one hour before delivery, the full benefits of 15-minute ISP is difficult to achieve, as there will not be opportunity for Market participants to balance their positions as close to real time as possible. Although trading on fine resolution can occur earlier, there is long time of uncertainty for market participant between the cross-zonal gate closure and quarter of delivery.

To address the second research question, the 15-minute auction trading is believed to reduce amount of structural imbalances resulting mainly from demand but also from solar power production in Nordic power system. The availability of consumption meter data on 15-minute resolution in Nordics greatly supports the likelihood of this finding. In order to reduce the amount of stochastic imbalances resulting from wind power production in the system a continuous intraday market is needed with fine resolution and with gate closure close to delivery. Thus, the responsibility of system balancing is expected to shift towards market participants, and the more open intraday markets are, the better balancing can be done by market participants.

To address the third research question, depending on market design and market coupling of Nordics to other markets, the 15-minute ISP can potentially open possibility to trade in finer resolution over HVDC interconnectors. The introduction of 15-minute products over HVDC interconnectors might not bring large market coupling benefits, but they may potentially overrule the current ramping restriction around the hour shift. In such case, the interconnector flows will be ramped over the whole hour, with a smaller ramp rate. This will greatly reduce the imbalance jumps over the HVDC interconnectors, and coupled with systematic imbalance trading in intraday auctions, will greatly reduce need for balancing around hourly shift and the frequency quality in Nordic power system may be improved.

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